HYDRAULIC AIR COMPRESSORS

By Leroy E. Schulze

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Leroy E. Schulze[1/]

CONTENTS

	Page
Introduction	1
Summary of the seven installations in the United States and Canada	1
Acknowledgment	4
History	4
Details of United States and Canadian installations	8
Taylor Hydraulic Air Compressing Co., Ltd., Montreal, Quebec, Canada	8
Dominion Cotton Mills Co., Ltd., Magog, Quebec, compressor	8
Kootenay Air Supply Co., Coffee Creek (near Ainsworth), British Columbia	10
Cascade Range, Wash., installation	10
Continental Compressed Air Power Co., Norwich, Conn., installation	11
Trent Canal Hydraulic Lift Lock No. 1, Peterborough, Ontario	11
Victoria Copper Mining Co. compressor installation, near Rockland, Mich.	12
Cobalt Hydraulic Power Co., Cobalt, Ontario, installation	18
United States and Canadian inventors	20
Foreign installations and inventors	20
Germany	20
Dillingen test installation	21
Glanzenberg-shaft test installation	22
Holzappel mine at Laurenberg	23
Royal mine-inspection plant at Clausthal	24
Royal mine-inspection plant at Grund (in the 4th light shaft)	24
Compressor at Zeche Victor Rauxel at Dortmund	25
Review of experiences and operation of the Harz Mountains compressors (1921)	25
Sweden	27
Persberg Mine Co. compressor	27
Falun Mine compressor (in the Bergslagen iron-mining district)	29
Installations by J. O. Boving, London, England	31

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CONTENTS (Con.)

	Page
Loss due to solution of air in water under increasing pressure.	32
Possibilities for application	33
Conclusion	34
Bibliography	35
Patent List	38

TABLES

1.	Results of experiments in compressing air by causing it to mix with a descending current of water	7
2.	Results of trials of the Taylor hydraulic air compressor at Magog, P. Q., by Prof. C. H. McLeod	9
3.	Results of several trials of Taylor's hydraulic air compressor at Magog, Quebec	9
4.	Test data, Dillingen unit	21
5.	Test data, Glanzenberg unit	22
6.	Test data, Glanzenberg unit	22
7.	Test data, Glanzenberg unit	23
8.	Test data, Holzappel unit	24

ILLUSTRATIONS

Fig.		Follows page
1.	Sketch of Frizell shaft, St. Anthony Falls, Minn.	4
2.	Sketch of Frizell's patent drawing	4
3.	Photograph of Taylor hydraulic air compressor, Dominion Cotton Mills Co., Magog, Quebec	8
4.	Sketch showing features of Magog installation	8
5.	Arrangement of compressor in breastwall	12
6.	Details of headpiece and air separator, Trent Canal, Peterborough, Ontario	12
7.	Trent Canal Hydraulic Lock No. 1, Peterborough, Ontario.	12
8.	View showing Victoria Dam built in 1930 for hydroelectric power, original canal to air compressor under water since 1930, and plume of the compressor's safety blow-off, Victoria Mining Co., near Rockland, Mich.	12
9.	Stamp-mill building, Victoria Mining Co	14
10.	Air-operated stamp head, Victoria Mining Co	14
11.	Jigs, Victoria Mining Co	14
12.	Intake heads, Victoria Mining Co	14
13.	Drawing of assembly of headpiece, showing sectional bustle pipe with air-inlet pipes, Victoria Mining Co.	16
14.	Condition of intake heads in 1949, Victoria Mining Co.	16
15.	Ice tower formed by discharge of air and water from safety blowoff during winter, Victoria Mining Co.	16
16.	How a "blowback" wrecked intake building, Victoria Mining Co., about 1914	16
17.	Interior of air chamber, showing three steel tubes at bottom of fall shafts, Victoria Mining Co	16
18.	Condition of intake heads, Victoria Mining Co	16
19.	Condition of the steel supporting frame, Victoria Mining Co	16
20.	Condition of the discharge opening, Victoria Mining Co.	16

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Fig.		Follows page
21.	View of blowoff geyser from the 12-inch safety blowoff pipe, Victoria Mining Co.	16
22.	General sectional view of air compressor (drawn by Taylor in 1903)	16
23.	View of interior of air-separating chamber looking toward inlet, before compressor operation, Victoria Mining Co., 1906	16
24.	View of interior of air-separating chamber looking toward discharge end before compressor operation, Victoria Mining Co., 1906	16
25.	Cobalt Hydraulic Power Co. compressor intake head being lowered during construction, in 1910	18
26.	Compressor intake heads in operation, Cobalt Hydraulic Power Co	18
27.	General view of intake building and spray from safety blowoff pipe, 1945, Cobalt Hydraulic Power Co. compressor plant	18
28.	Cobalt Hydraulic Power Co. compressor-design details, taken from general construction drawings by Chas. H. Taylor, 1909	18
29.	Cobalt Hydraulic Power Co. compressor-valve-house equipment in operation, winter of 1949	18
30.	Cobalt Hydraulic Power Co. compressor safety blowoff pipe in operation, 1945	18
31.	Details of Dillingen test installation, Dillingen Iron Works, Germany	20
32.	Arrangement of Holzappel compressor, Holzappel mine, Laurenberg, Germany	20
33.	Clausthal compressor, Altensegen shaft, Royal mine plant, Clausthal, Germany	24
34.	Drawing of Grund compressor, 4th light-shaft, Royal mine plant, Grund, Germany	24
35.	Reproduction of a photograph of the Grund intake construction, Grund, Germany	24
36.	Drawing of Persberg compressor showing tower, conduit, intake head, and fall tube, Persberg Mine Co., Sweden	24
37.	Persberg compressor, Persberg Mine Co., Sweden	28
38.	Suction head, Persberg Mine Co., Sweden	28
39.	Persberg Mine Co., Sweden	28
40.	Suction head and air-separator design, Falun mine	28
41.	Falun mine compressor, general arrangement	28

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INTRODUCTION

A review of development and a reevaluation of uses of the hydraulic air compressor are suggested by the constant changes in technology, which frequently make an old art valuable in solving current problems. Contacts with research workers in various branches of engineering indicate that this older method of producing compressed air may not be familiar to some or that its salient features might be useful in solving problems involving uses of compressed air. Briefly, a hydraulic air compressor may be described as an inverted siphon, consisting of an intake head where water and air are mingled, followed by a gravity-fall tube in which air is intimately mixed with the water and is compressed as the water pressure increases during the fall down the tube, then a separating, or stilling, chamber in which air bubbles rise to the surface of the water and collect in the upper portion of the chamber at a pressure equal to the waterhead maintained by the height of water in the discharge leg of the circuit. The water, which now contains only the fraction of air that has gone into solution, passes out of the separating chamber and rises up the discharge leg to the surface, which is, of course, at some suitable distance below the level of the intake. Present-day applications include (1) utilizing low hydraulic heads, which otherwise have little commercial values; (2) utilizing low hydraulic heads in reclamation work to supply compressed air, or in some instances to produce a small suction, for air-lift pumping (or for operation of air motors), with minimum attendance and without need for electric power; (3) utilizing medium heads, as at dam and lock installations, to produce compressed air for pneumatic operation of airlifts, gates, valves, and rubber gate seals; (4) utilizing underground waters, as in mines, to produce compressed air for general mine use; (5) using this method of isothermal compression of air in combination with standard compressors wherever hydraulic head is available, thereby securing the advantages of low-temperature intake to the mechanical compressors and reduction of moisture content below that of atmospheric air; (6) development of large air supply at pressures up to 150 p.s.i.g., which, after performing work in reciprocating or centrifugal expansion cylinders, is available at temperatures approximating -50° F. Possibilities in freezing and reheating should be mentioned which may prove economical for obtaining uniformly dry air for process work, wind-tunnel tests, or large air-conditioning installations, such as ventilation of underwater traffic tunnels, and may be economic for supply of supercharged air to gas-turbine plants.

SUMMARY OF THE SEVEN INSTALLATIONS IN THE UNITED STATES AND CANADA

The several installations of hydraulic air compressors in the United States and Canada (a few units remain in constant operation though constructed from 1896 to 1910) were principally the result of persistent work by Chas. H. Taylor of Toronto, Ontario (deceased). Taylor was responsible for the first commercial installation at the Magog, Quebec, plant of the Dominion Cotton Mills Co. (now Dominion Textile Co., Ltd.), which went into operation in August 1896. The initial operation of this

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compressor attracted the attention of many competent engineers. On August 7 and 13, 1896, Prof. C. H. McLeod (of the faculty of Applied Science, McGill University, Montreal) made 6 tests of the Magog compressor (table 2). Prof. W. C Unwin (of the engineering faculty of Guild's Central Technical College, London, England) visited Magog in September 1897 and reviewed McLeod's report of the tests and concurred in the conclusions drawn. He further expressed the opinion that the future of the compressor was favorable and that improvements could be made to raise the efficiency to approximately 75 percent. About 1901 the Magog installation was dismantled to permit development of hydroelectric power, which proved to have more ready adaptation to various power demands of the textile plant.

In 1897 the Taylor Hydraulic Air Compressing Co., Ltd., Montreal, arranged for an affiliated company, Taylor Air Compressing Co., Ltd., Spokane, Wash., to handle rights to the invention in Washington, Idaho, and Montana and in British Columbia. The Spokane company acquired the Kootenay Air Supply Co., British Columbia, and shortly thereafter began work on a compressor installation at Ainsworth, British Columbia. Mines that this unit was to supply were forced out of operation by a change in production and freight costs. Although the compressor was reported to have been in operation in 1911, no information is available as to its final disposition, and it is presumed that it was left to deteriorate.

The Spokane company advertised in 1897 that a 2,000-hp. unit was being planned for the mining area around Rossland, B.C. There is no record available that this installation was made.

In April 1899 Prof. J T Nicolson, of McGill University, Montreal, conducted some new tests at Magog (10h).2/ Among witnesses were J A Inslee, St. Louis, Mo., A. Johnson, Richmond, Va., and W. O. Webber, Boston, Mass. The latter obtained several patents on compressor improvement features and wrote extensively on the subject. Webber reported in 1900 (12) that three plants were then under construction at Norwich, Conn., at Peterborough, Ontario, and at an isolated location in a canyon in the Cascade Range, Wash.

During September 1899, additional tests were made at Magog (10d) by engineers of Continental Compressed Air Power Co., Philadelphia, Pa., which led to their decision to construct a plant on the Quinebaug River at Taftville about 3 miles above Norwich, Conn. This installation had the largest downflow pipe used in any of the installations, 14-inch diameter, but the horsepower was limited owing to variable river flow. Air was supplied to industry at Norwich through a 16-inch cast-iron pipeline about 4 miles in length. This plant was replaced by a hydroelectric plant in 1929.

The Peterborough, Ontario, installation was completed in 1904 and has been in operation during the canal operating period from May through October each year since that time. Air at about 25-pound gage is used in air-lift dewatering of the large press wells and to inflate seals on the lock chamber gates (14b).

The Cascade Range installation mentioned by Webber in 1900 has been unreported in the literature and may never have been completed.

The next installation made by Taylor was at the Victoria Copper Mining Co., at Glenn Falls on the Ontonagon River about 4 miles west of Rockland, Mich. Thomas

2/ Underlined numbers and letters in parentheses refer to reference list in bibliography at the end of the report.

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Hooper, superintendent and manager of Victoria, inspected the Norwich installation in 1903 and concluded that the results there justified confidence in the plan for Victoria. Construction, which included the storage pond, the dam and locks, the canal to the compressor plant, and the water tunnel to the stamp mill, in addition to work in the mine proper, was begun in 1904 but was not completed until March 9, 1906. Operation was virtually continuous until the mine closed in 1921 owing to the decline in the price of copper. From 1921 until 1929, the unit operated as a manmade geyser attraction for tourists. Its blowoff line spouted a plume of water some 500 feet into the lower river gorge. In 1929 the compressor was reconditioned enough to supply compressed air during construction of Victoria Dam of the Copper District Power Co. (now Upper Peninsula Power Co.). Lack of attention during extreme cold in the winter of 1934 caused the safety blowoff to plug and air to accumulate in the storage chamber and finally blow back up the intake tubes, wrecking the intake shafthouse. Since that time the entire installation has deteriorated and filled with debris, although it is still possible to inspect the principal parts of the installation.

The last installation was made in 1910 by the Cobalt Hydraulic Power Co. at Cobalt, Ontario, to supply compressed air to mines in that area. An elaborate transmission line, which at the peak of mining activity required nearly 100 miles of pipe, including 20-inch-diameter mainline and branches of smaller sizes, was installed on supports to permit it to traverse the rugged terrain of the area. The pipe was largely seamless, with forged, flanged ends and was imported from Germany. A successor company, the Northern Ontario Power Co., operated this installation as well as other electric generating plants in the area until acquired by The Hydroelectric Power Commission of Ontario in 1944. It is still in constant operation, and consideration is being given to cleaning and reconditioning the compressor and to repairing the transmission line and branches, which leak badly. Air bubbles are visible as they issue from cracks in the rock of the river bed above the huge compressed-air storage chamber, and leaks in the pipelines are readily audible in the second-growth timber where pipe lines lead to mines still in active operation. Special airmeters, built in 1910, are of questionable accuracy, and the overall efficiency of the compressed-air installation is quite low.

Appropriate to this short summary would be the mention of work done by men before Taylor and also since his last installation at Cobalt. J. P. Frizell, Boston, Mass., studied the method of compressing air and obtained the original patent (199,819) on January 29, 1878, on Method of Compressing Air. Frizell constructed the first experimental model of his invention at St. Anthony Falls (then the village of St. Anthony), Minneapolis, Minn., in 1880 and reported in detail on his results (5). J. G. Pohle, Georgetown, Colo., obtained two patents in 1886 on means of lifting water by compressed air, which is essentially the reverse of the function of the air compressor. He continued experimental work on the "airlift" in San Francisco in cooperation with the firm of Rix & Firth until at least 1889 (22h). In 1890 a Mr. Priestly (22e)(not otherwise identified) constructed a combination hydraulic air compressor and air-lift pump to raise water from a ledge on the north cliff wall of the Snake River at a point known as Thousand Springs, near Hagerman, Idaho (now the Thousand Springs plant of Idaho Power Co.). Priestly lifted the water to the top of the cliff to supply irrigation to his land adjoining the cliff. His installation was crude and faulty in its construction and hard to maintain. It was dismantled in a few years. Priestly probably made use of the inventions of Frizell and Pohle, because his construction appears to be a combination of the work of both. The flow from Thousand Springs was gathered in a flume (constructed in 1911 (22f)) and supplied a penstock leading to the 2,500-kv.-a. hydroelectric plant of the Thousand Springs Power Co. Considerable interest developed in Europe,

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particularly in Germany, from 1899 to 1921, and in Sweden from 1911 to 1926, when a number of commercial units was constructed. Some are still operating.

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HISTORY

The literature contains many references to the very old form of air compressor known as the trompe, which was used at the Catalan forges in Italy about 1640 (1a). The idea probably was carried to other parts of the continent, as there is evidence of its use in the Vosges and the Pyrenees Mountains in France and Spain. An account of finding an old installation, probably showing Spanish influence, near a trail leading into Tegucigalpa, Honduras, Central America, is given by C. F. Spalding (1b). This installation, used to supply low-pressure air to a copper smelter, was built with a nest of 14 bamboo pipes, each 6 to 10 inches in diameter, all packed tightly with clay, in a vertical shaft dropping about 40 feet down to a crude air-separator room.

The limitations of the trompe were of little consequence to the problems of that day, because the air was used to replace the hand bellows, which created only about 1 p.s.i. Still earlier, Heron of Alexandria in his Spiritalia and Pliny in his Natural History mention the trombe or trompe. Other uses of air were well understood earlier than 100 B.C. and served to manipulate religious devices used by the Egyptian and Pharaonic priests.

The first successful air-compressor plant was developed by Sommeiller in 1861 during construction of the Mont Cenis tunnel in the western Alps (2). It was a modified form of the Montgolfer hydraulic ram. In 1889, H. D. Pearsall reported (3) his improvement on Sommeiller's design by softening the ram blow and increasing the efficiency. In 1877, J. P. Frizell, member of the Boston Society of Civil Engineers, published his studies and theory of the direct compression of air by means of water falling through a small head (4), with means for separating the air from the water in a chamber, and the development of high air pressures through the action of the hydrostatic head of the discharge column on the separating chamber. Frizell filed his patent application on November 20, 1877, and United States Patent 199,819, Method of Compressing Air, was issued on January 29, 1878. That year at Massachusetts Institute of Technology, assisted by Prof. Whitaker, Frizell built and demonstrated small-scale models, but he was unable to test his design on any scale that would indicate its potential value until 1880. One model operated at only about

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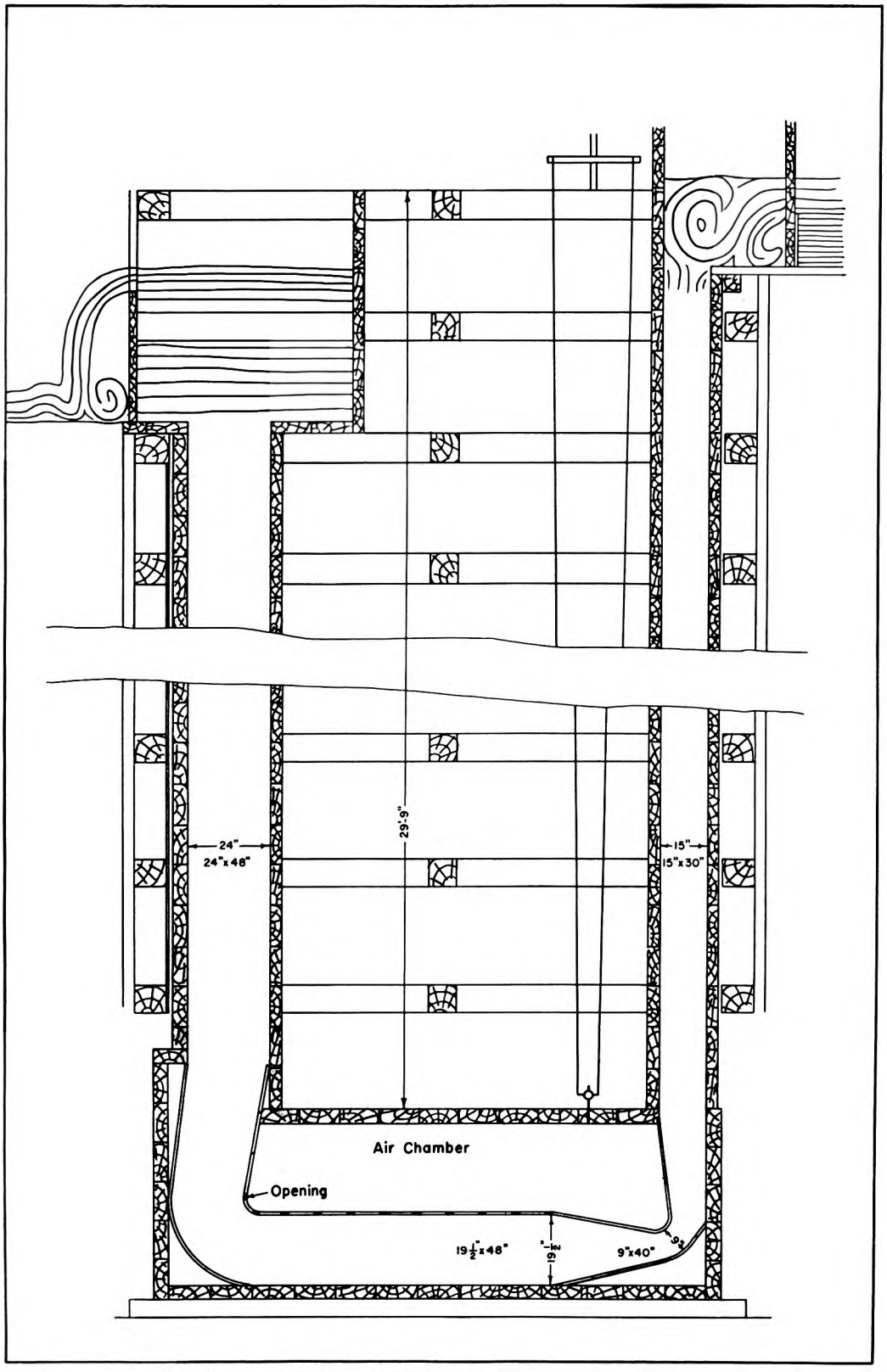

Figure 1. - Sketch of Frizell's shaft, St. Anthony Falls, Minneapolis, Minn. (Reproduced from publication Experiments on the Compression of Air by Direct Action of Water by J. P. Frizell, 1880.)

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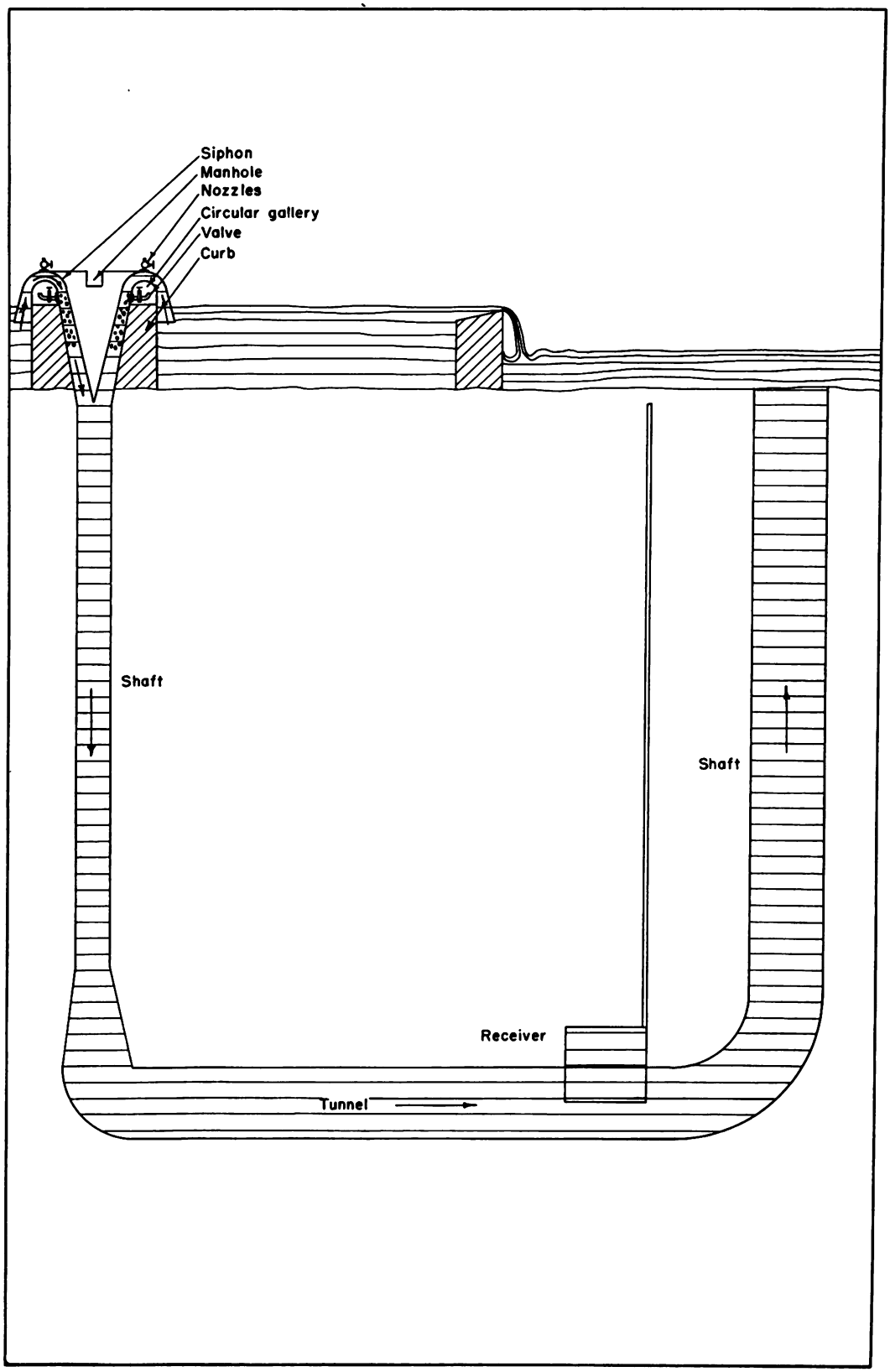

Figure 2. - Sketch of Frizell's patent drawing. (Reproduced from publication Experiments on the Compression of Air by Direct Action of Water by J. P. Frizell, 1880.)

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10-percent efficiency when using 1-1/4-inch-diameter tubes; and another, using 3-inch-diameter tubes and only 25 inches of waterhead, gave 26.5-percent efficiency. These results, though discouraging, and, quoting Frizell, "accepted by the unthinking as a failure of the method," served only to stimulate him into further work on a larger scale. During a visit to St. Paul, Minn., on other engineering work in 1880, Frizell learned of a dry shaft on a narrow island in the Mississippi River at the Falls of St. Anthony (now St. Anthony Falls in Minneapolis, Minn.). Through the courtesy of S. H. Chute, one of the owners of the St. Anthony Water Power Co., Frizell was allowed to use the shaft and to divert water from the river for his experiments. The shaft was part of the construction work by United States Engineers Corps from 1870 to 1876 (6), when they were successful in stopping the erosion of the limestone ledge, which would have destroyed the falls and the resulting power obtained from it. During the construction work the United States Engineer Corps cast a concrete dike completely across the river in the sandstone stratum that occurs just below the limestone ledge rock that forms the falls. This dike was hollow, with a manway to permit work and future inspection, and the dry shaft was the means of access to this manway. The shaft, still to be seen on the island, was about 6 by 14 feet inside the cribbing and about 36 feet deep. It was, at that time, easily connected by raceways to the millponds, on either side of the island, thereby providing a working head of 8 or 10 feet, which was adequate.

The story of the ill-conceived Eastman tunnel, which will be of interest to hydraulic engineers, appears worthy of discussion in connection with the above work done by the United States Engineers Corp authorized by action of Congress in 1870. W. W. Eastman, owner of a building site on the lower end of Nicollet Island (some distance above Hennepin Island and the above mentioned falls), proposed making his site suitable for power purposes by driving a tunnel from below the falls, under the limestone ledge, and up river to Nicollet Island. He began work in September 1868 and had it nearly finished by the fall of 1869, but at that time water in rapidly increasing amounts found its way into the tunnel and the diversion of the water disclosed the unknown fact that the limestone ledge terminated between the two islands. Large pieces of limestone, and ultimately several sawmills and other industrial buildings on the northern end of Hennepin Island, caved into the growing hole. By heroic effort of the citizens, loads of hay, timber, stone, and anything else that could be used to plug the widening opening were hastily dumped into the water. A cofferdam was erected to divert the river flow, and the balance of the industrial part of the island was saved. The discovery of the termination of the limestone ledge was alarming to the industrialists who relied on the waterpower for their mills, and an immediate appeal to Congress was begun.

Funds were provided for the project, which was directed by United States Engineer Corps; and work costing up to $800,000, including private contributions by millowners, was carried out from 1870 to 1883.

Details of the Frizell shaft, with its cribbing and interior construction, are shown in figure 1. By comparing the shaft construction (fig. 1) with the more ideal proportions shown in his patent drawing (fig. 2), it can be seen that Frizell was handicapped by the short length of the air-separating chamber. Frizell recognized that a longer chamber would have provided extended travel time for the water and permit more complete air separation, with resultant higher efficiency of air recovery.

Examination of figure 2 and a study of the patent specification indicate that Frizell did not contemplate a means of adjusting the position of the siphon or suctionhead with respect to the level of the forebay. His construction also required an air pump, attached to nozzles (fig. 2) to start the siphoning action. With these

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exceptions, Frizell's design was basic for the later work of Taylor in 1894. Taylor made the suctionhead adjustable so as to start air entrainment by lowering into the water and stop it by raising the suctionhead out of the water.

Frizell's tests were conducted in May and June 1880. He arranged a means for indicating when the air chamber was filling to a calculated volume; he determined the degree of water lost through the planking when under pressure and allowed for it in his calculations; he also determined the resistance of the hydraulic circuit when no air was entrained and used a factor for related resistance at other velocities of flow. Some of his calculations were general rather than specific; but, since he desired only "substantial accuracy" at this stage, he did not make all of the refinements that later commercial work would justify. The air chamber was under a slightly variable head of 27.46 to 30.08 feet. He did not consider the effect of solubility, although he was well aware that it would influence results in any carefully conducted work. Frizell admits that his calculation of power in the air compressed is not completely accurate, nor is his determination of the atmospheric pressure, because he used 34 feet of water in the calculations. He was aware that the error was on the conservative side, since the upper pool was about 799 feet above mean sea level and barometric fluctuations would have to be considered in a completely accurate calculation. Nevertheless, his results are interesting and table 1 gives them as taken from his report (5).

Review of conditions that caused the water to entrain air indicates that Frizell was handicapped by the limited velocity of water descending in the shaft, which was about 3.0 feet per second, for he found at any higher velocity that some of the contained air in the water chamber continued with the water and escaped up the rising shaft. It is apparent that the plank separator between the air chamber and the water chamber was not entirely adequate because some air could readily pass along the under surface of the planking of the separating wall and thereby escape with the water. Frizell was undoubtedly aware of the various limitations of his compressor construction and of the results obtained, but his report did not go into further detail.

Calculated efficiencies of 40.4 to 52.1 percent were obtained, which were encouraging to him as indicating progress. Frizell then speculated on the probable efficiency to be obtained in a more ideal design of larger size. He believed he could secure an efficiency of 76 percent by using a 15-foot fall, a velocity in the descending shaft of 6 feet per second, a shaft 10 feet in diameter extending to a depth 120 feet below tail-water level, which would provide about 50-pound-gage pressure. With a 30-foot fall and a shaft having a depth of 250 feet below tail-water level (resulting in about 100-pound-gage pressure), he estimated he could obtain 81-percent efficiency.

As a hydraulic engineer, Frizell was prominent, and his book, Waterpower (8), filled a definite need in the technology of that day. Frizell had a practical understanding of the more elusive problems involved in the hydraulic air compressor, as shown by his discussion of Loss Due to Solution of Air (8, p.475).

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TABLE 1. - Results of experiments in compressing air by causing it to mix with a descending current of water

Number of experiment	Date, 1880	Head, feet	Pressure on air in chamber, in feet of water	Quantity of water, cubic feet per second	Quantity of air carried into chamber, cubic feet per minute	Power due to 1 cubic foot of air, foot-pounds	Total power of air for 1 minute, foot-pounds	Total power of water for 1 minute, foot-pounds	Percentage of useful effect	Velocity in the descending shaft, feet per second
1	May 30	4.07	28.58	9.45	27.60	2,528.3	69,781	143,780	48.5	3.02
2	30	3.24	29.43	9.89	18.59	2,627.4	48,843	119,780	40.8	3.16
3	30	2.62	30.08	9.45	14.47	2,703.2	39,115	92,549	42.3	3.02
4	31	2.54	29.91	5.92	8.53	2,683	22,877	56,207	40.4	1.89
5	31	.98	-	14.03	.00	-	-	-	-	4.49
6	31	4.82	27.68	10.34	31.40	2,426.3	76,193	186,297	40.9	3.31
7	31	4.70	27.75	11.89	38.07	2,434	92,668	208,890	44.3	3.80
8	31	4.77	27.75	11.89	35.95	2,434	87,522	212,000	41.3	3.80
9	31	4.81	27.72	11.22	42.12	2,430.7	102,391	201,733	50.7	3.59
10	31	4.87	27.68	10.34	36.89	2,427.2	89,529	188,230	47.6	3.31
11	31	4.94	27.58	8.23	27.31	2,415.2	65,951	151,973	43.4	2.63
12	June 2	4.78	27.64	9.46	34.90	2,422	84,519	169,040	50.0	3.03
13	2	4.79	27.64	9.46	36.41	2,422	88,200	169,381	52.1	3.03
14	2	5.01	27.47	6.10	21.42	2,402.7	51,476	114,237	45.0	1.95
15	2	5.02	27.46	5.92	21.44	2,401.9	51,503	111,090	46.4	1.89

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DETAILS OF UNITED STATES AND CANADIAN INSTALLATIONS

Taylor Hydraulic Air Compressing Co., Ltd., Montreal, Ontario, Canada

From 1880, when Frizell reported on his work at St. Anthony Falls, little active interest is reported in the literature on the subject of hydraulic compressors until 1893 when Chas. H Taylor built a small model in his shop in Montreal. He interested several local businessmen in financing his work. On July 23, 1895, he obtained three United States patents (543,410-411-412) to cover various features of design. Before these patents were issued, the Taylor Hydraulic Air Compressing Co., Ltd., had been organized and was building its first commercial unit at the Magog, Quebec, plant of the Dominion Cotton Mills Co. Taylor presumably obtained Canadian patents covering the same features as his United States patents.

Dominion Cotton Mills Co., Ltd., Magog, Quebec, Compressor

Only a brief summary will be made here of the Magog installation, since a great deal has been written to which reference may be made (10). Figures 3 and 4 show a photograph and a drawing of the Magog compressor as taken from some of the Taylor company literature. Table 2 presents data obtained by Prof. McLeod of McGill University during a test of the Magog compressor in 1896. Table 3 lists values obtained during tests and by calculations by Prof. McLeod and used as advertising information by the Taylor company.

Dimensions of the unit shown in figure 4 will give an idea of the proportions of this unit. The penstock (A) is 5 feet 6 inches in diameter and is connected to the head tank (B), which is 12 feet in diameter. Inside this head tank is a hand-operated suctionhead piece with 34 tubes, each 2 inches in diameter, the upper ends of which are above the water level, whereas the lower ends extend into the flow of water passing over the lip of the suction tube. Air is sucked through these 2-inch-diameter tubes by the passage of water and is entrained with the water as it enters the top of suction tube (C). Tube C is 3 feet 8-1/2 inches in diameter and extends down a 10- by 10-foot shaft (E), flaring slightly to 4 feet 8 inches in diameter at the entrance to the top of separating tank (D). The combination separator and air-storage tank (D) is 17 feet in diameter and 10 feet high. The water then flows out at the bottom of tank (D), rises in the shaft (E), and is taken away by the tail-race (F). Air is separated by the baffle plate (K), which provides a longer path for the water, and rises to the water surface being conducted out of tank (D) by airline (I) to valve (P). Other control lines are usually included, such as the one at (H), which shows that air-storage volume has reached a point at which the suctionhead piece should be raised and air intake thereby reduced. This is to prevent air from accumulating in the storage space and forcing the water level down to a point at which a blowback up the compression tube (C) may occur.

In conducting his tests, Prof. McLeod noted that the average water column in the shaft, which provided the compression pressure of the air in the tank, was 120.5 feet, which he stated was equivalent to a gage pressure of 52 p.s.i. McLeod measured the water quantity in the tailrace with an electrical recording current meter, which had been carefully rated. He took readings at 4 equally spaced vertical sections in the 12-foot-wide tailrace and at 3 points in each section. The delivered air was measured by anemometers placed in a discharge pipe at a point where the cross section had been gradually increased to about 1 square foot. During the tests, McLeod used about 22 feet of effective hydraulic head and varied the water quantity from 4,000 to 7,600 c.f.m. He calculated an efficiency of 62.4 percent at the 4,000-c.f.m. flow and 50.8 percent at a flow of 7,660 c.f.m.

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Figure 3. - Photograph of Taylor hydraulic air compressor, Dominion Cotton Mills Co., Magog, Quebec.
(Reproduced from advertising literature of the Taylor Hydraulic Air Compressor Co.)

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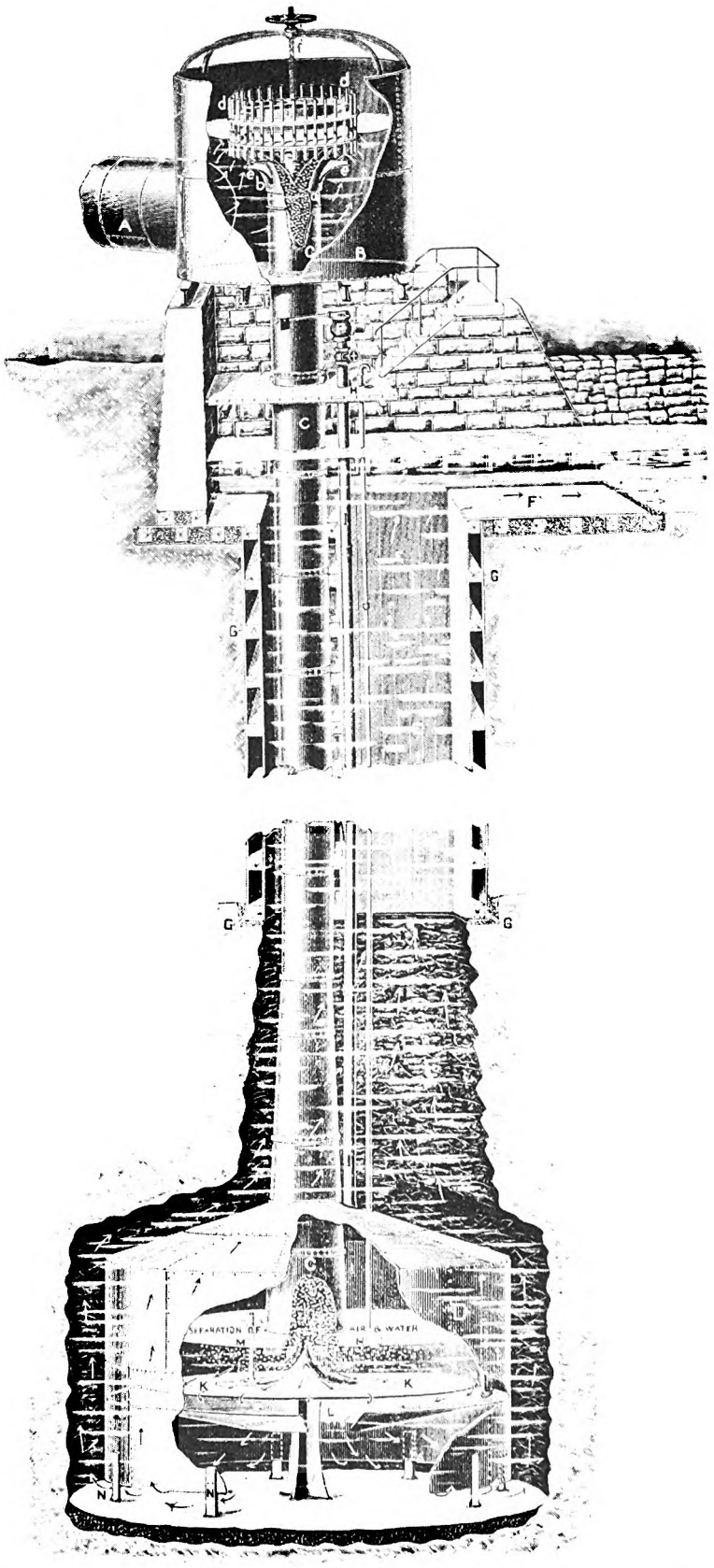

Figure 4. - Sketch showing features of Magog installation.

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TABLE 2. - Results of trials of the Taylor Hydraulic Air Compressor at Magog, P.Q., by Prof. C. H. McLeod

Number of trial	Quantity of water discharged, cubic feet per minute	Available head, feet	Available horsepower	Quantity of air delivered, cubic feet per minute at atmospheric pressure	Pressure of air in compressor, p.s.i.	Actual horsepower of compressor	Efficiency of compressor	Temperatures, °C.		
								External air	Water	Compressed air
I	II	III	IV	V	VI	VII	VIII	IX	X	XI
1	6,122	21.4	247.7	1,377	52	132.5	53.5	79	75.2	75.2
2	5,504	21.9	228.0	1,363	52	131.0	57.5	83	75.5	75.5
3	4,005	22.3	168.9	1,095	52	105.3	62.4	80	75.6	75.6
4	7,662	21.1	305.9	1,616	52	155.4	50.8	75	80.0	80.0
5	6,312	21.7	260.0	1,506	52	144.8	55.7	77	80.0	80.0
6	7,494	21.2	299.8	1,560	52	150.2	50.1	75	80.0	80.0

TABLE 3. - Results of several trials of Taylor's hydraulic air compressor at Magog, Quebec

	1	2	3	4	5	6	7
Water discharged.....cubic feet per minute	6,122	5,504	4,005	7,662	6,312	7,494	4,000
Available head.....feet	21.4	21.9	22.3	21.1	21.7	21.2	22.0
Available horsepower.....	247.7	228.0	168.9	305.9	260.0	299.8	-
Air delivered at atm. pressure.....cubic feet per minute	1,377	1,363	1,095	1,616	1,506	1,560	1,250
Pressure of air in compressor.....	52	52	52	52	52	52	52
Actual horsepower of compressor.....	132.5	131.0	105.3	155.4	144.8	150.2	-
Efficiency of compressor.....	53.5	57.5	62.4	50.8	55.7	50.1	75.12
Temperature of external air - August 1896.....°C.	79	83	80	75	77	75	-
Temperature of water.....do.	75.2	75.5	75.6	80	80	80	-
Temperature of compressed air.....do.	75.2	75.5	75.6	80	80	80	-
Ratio of water to air.....	4.45	4.04	3.66	4.75	4.20	4.80	3.2
Mean velocity of water down shaft..... feet per second	10.89	9.89	6.98	13.50	11.28	12.62	7.42
Mean velocity of rising bubbles = 1.5 diameter.....do.	0.81	0.81	0.81	0.81	0.81	0.81	0.81
Loss due to air bubbles rising.....percent	7.48	8.14	11.67	6.03	7.22	6.45	10.63
Head equivalent to velocity lost at bottom.....	0.609	0.499	0.266	0.948	0.651	0.906	0.270
Head equivalent to velocity at entrance.....	0.576	0.478	0.241	0.893	0.620	0.758	0.279
Head equivalent to friction resistance in down shaft.....	2.117	1.754	0.874	3.245	2.278	2.893	1.749
Head equivalent to friction resistance in up shaft.....	0.038	0.031	0.021	0.061	0.041	0.073	0.016
Loss due to above hydraulic resistance, etc..... percent	15.61	12.61	6.29	24.38	16.54	21.73	10.97
Total losses calculated.....do.	23.09	20.75	17.96	30.41	23.76	28.18	21.60
Total losses due to inefficient separation.....do.	23.41	21.75	19.64	20.39	20.54	21.72	3.28

The final column is calculated so as to show how readily the efficiency would be raised by the more thorough impregnation of the water and effective separation, which can be obtained in future plants.

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As shown in table 3, McLeod calculated various losses in the hydraulic circuit, including the loss due to air bubbles tending to rise in the descending shaft. He suggested that the calculated efficiency could be greatly improved by better separation of the compressed air in the air chamber and pointed to an efficiency of 75 percent under those improved conditions. In later test (in 1899) (10b, 10g), in which an increased number of air tubes (15, 3/4-inch-diameter tubes added to the 34, 2-inch-diameter tubes) was used, a calculated efficiency of 70.7 percent resulted.

Kootenay Air Supply Co., Coffee Creek (near Ainsworth), British Columbia

The Kootenay Co., acquired by the Taylor Air Compression Co., Ltd., of Spokane, Wash., in 1897, installed the second Taylor-type air compressor in 1898. It began operation in April 1900, supplying air at approximately 85-p.s.i.g. pressure to about 15 mines (11b). The water supply was conducted about 1,350 feet through a 5-foot-diameter wood-stave pipe to the compressor location, which was at a cliff face where 107.5 feet of hydraulic head could be obtained. The suction tube and its head tank were mounted on a wooden supporting structure built against the face of the cliff. The head tank, which contained the headpiece and the upper end of the suction tube, was of wood-stave construction and was 12 feet in diameter and 20 feet high. The suctionhead, or funnel, was made of iron and was 7 feet in diameter. Suspended above the suctionhead was a tube nest consisting of 3,000, 3/4-inch-diameter air tubes, which during operation had their lower ends in the water flowing over the lip of the suctionhead. It was estimated the water and its entrained air dropped down the suction tube at a velocity of 34.5 feet per second through the 2-foot 9-inch-diameter wood-stave portion of the suction tube for about 107 feet and then continued vertically 210 feet down a shaft of about 32-square-foot cross section, which also served as the rising shaft for the discharge water from the air separator. At the bottom of this shaft was the air-separator chamber, constructed of steel plate 17 feet in diameter and 17 feet high. The suction tube entered this chamber on the side and produced a vortex in the separator. This construction was the result of suggestions by McLeod for improving air separation. No tests are available on operation of this compressor, although the Taylor company reported that, with a water supply of 4,200 c.f.m. and a head of 107.5 feet, 85 cubic feet of free air was entrained per second, which was compressed to 12 cubic feet at 87 p.s.i.g. pressure, and this was calculated as being equivalent to 465 hp.

The only article that is available (11d) as to the operation of this unit indicates it was still in use about 1911. Davis' article gives some figures from memory, such as an efficiency of 55 percent, with an air volume of 5,000 c.f.m. free air produced. Water horsepower was recalled as being 600 hp. The cost of construction was approximately $60,000.

Cascade Range, Wash., Installation

This installation was also made by the Taylor Air Compression Co., Ltd., Spokane, Wash., in 1901. It was similar to the Kootenay design in that it was built near the face of a cliff. It did not, however, have a shaft into which the downflow pipe was introduced; instead, the entire compressor was exposed vertically along the cliff face. It operated from a 45-foot hydraulic head (12), and its 3-foot-diameter compression pipe (downflow pipe) dropped 245 feet into the separating chamber from which a 4-foot 9-1/2-inch-diameter upflow pipe extended 200 feet vertically to its discharge point. The resultant air pressure in the chamber was approximately 85 p.s.i.g. The available water was estimated at 2,000 miners' inches (3,000 c.f.m.) in the paper by Webber, and it was stated the compressor would deliver about 200 hp. How long this unit operated is not known.

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Continental Compressed Air Power Co., Norwich, Conn., Installation

In 1899 a number of engineers from the United States witnessed the tests conducted by McLeod at Magog. The favorable results of these tests led them to proceed with construction of the compressor at Norwich, Conn. J. H. Shedd, consulting engineer, of Providence, R. I., and W. O. Webber, of Boston, Mass., were in charge of the design and construction of the dam and compressor (13a). The site chosen for the installation was on the Quinebaug River near Taftville, Conn., at a point where it entered a gorge known as Tunnel Privilege. Work on the dam was begun in October 1899 and on the compressor in April 1901. The installation was substantially completed in July 1902. The literature (13a, 13b) contains relatively little about the compressor or its efficiency but directs attention to the novel features of the automatic flash boards designed for the dam. These were necessary to safeguard the railroad track, which paralleled the river channel at this point, from flash floods due to rapid changes in river flow or compressor operation.

The compressor, designed by Webber, was arranged for part capacity by separators in the suctionhead and included an inverted "V" form of air bar rather than the tube-nest design used by Taylor for introducing air into the waterflow. The downflow pipe was 14 feet in diameter, which made it easily the largest of all known compressor installations. Owing to the great variation in the riverflow, much of the time the compressor was using only a portion of the water, and at other times the flow was inadequate for air requirements. This condition led to dismantling of the installation in 1929 to permit construction of a hydroelectric power plant.

Shedd reports (13b) on the construction of the shaft and chamber for air separation and storage. The shaft was driven in solid rock to a depth of 208 feet below the riverbed. It was 24 feet in diameter and was reported to cost $3.50 per cubic yard for construction. At the bottom of the shaft a chamber 52 feet in diameter was constructed, which housed a steel shell to give the waterflow a chance to separate from the air. Connected to this separating chamber was a form of air-regulator reservoir which measured 18 feet in width and was 15 to 20 feet high and about 100 feet long. From the steel air-separator shell, a 16-inch, cast-iron air main extended about 4 miles to Norwich where a number of air engines was operated at about 90 p.s.i.g. Webber, judging from his patent specification No. 748,898 issued on January 5, 1904, found the large 14-foot diameter downflow pipe to have limitations with varying flow. He devised a means of subdividing the downflow pipe for operation at part flow. There is no information available that his designs were put into use in any other installation. Webber reports (16c) that in some experiments at Norwich he obtained entrainment of air with a head of only 0.7 foot on the intake and that air was carried down 187 feet with the water. No reports of efficiency tests on this compressor are available.

Trent Canal Hydraulic Lift Lock No. 1, Peterborough, Ontario

According to Webber (14a), construction on this unusual hydraulic-lift lock design was begun in 1900. The fact that a Taylor-type air compressor is incorporated into the breastwall of the dam is little known, except to local people. In fact, the writer found that some of the lock attendants were unfamiliar with the air compressor or how it was built; they knew only that, when water was admitted to the inlet at the upper channel, air came out of a pipe in the pumproom located in the breastwall. With little maintenance, this unit has delivered air from the time when it started in July 1904, running constantly during the period of lock operation

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from May through October each year (14b). By means of airlifts, air at about 25-p.s.i.g. is used for dewatering the large collecting wells under the lift chambers and for inflating pneumatic seals on the gates of the lift chambers. Some compressor construction details are shown in figures 5 and 6, which are taken from drawings supplied by Dominion Bridge Co., Montreal, general contractors for the superstructure of the lock, which alone is reported to have cost $240,000. This figure does not include the concrete work of the upper or lower canal or the massive breastwall, which measures 40 feet wide, 80 feet high, and 126 feet long at the base. The 40-foot width of the breastwall permitted construction of a large pumproom entirely within the wall, and also a 14- by 21-foot tunnel for traffic along Hunter Street. During the construction of this breastwall the air-compressor parts were cast in place, and except for a small access plate in the top of the wall one would be unaware of its existence. Figure 7 is a recent winter view of the lock, with lift chambers in winter position to avoid ice damage. This lock is reported to be the highest hydraulic-lift lock in the world and is 1 of 2 such locks in operation on the 240-mile-long Trent Canal. The Canadian lift locks are quite different from the smaller lift locks built in England, France, and Belgium during the 19th century, because they are adapted to the severe winter condition of the area and make use of steel-construction methods available to designing engineers at the time.

The compressor is reported capable of delivering continuously 300 c.f.m. of free air at about 28 p.s.i.g. The excess air, above that needed for intermittent operation of the gate seals and the air-lift pumps in the presswells, is automatically released by a blowoff pipe shown in the drawings. Because the compressor was designed to render a special, intermittent service, which it does with little attention, there are no records of any tests being made as to its efficiency of operation.

It is of interest to note that in 1926, after the compressor had operated for 22 years without difficulty, the engineer in charge decided to provide a turbine-driven air compressor in anticipation of trouble developing. A hydraulic turbine driving a vertical two-cylinder air compressor was installed in the pumproom but has never been used, except to assure its operability. The Taylor-type compressor, meanwhile, continues to deliver all the air required from the time it is started when the lock opens in May until it is stopped in the fall.

Victoria Copper Mining Co. Compressor Installation, near Rockland, Mich.

The problem of obtaining a large supply of compressed air for mining requirements had been solved by another interesting compressor installation at Quinnesec Falls on the Menominee River 3 miles below Iron Mountain, Mich., in 1882 (15). A short description of that installation will be of interest here to contrast it with the Victoria compressor. The Quinnesec Falls unit was in operation at the time of construction of the Victoria compressor in 1905, thus a ready comparison was possible as to the merits of each type. The Quinnesec Falls compressor station consisted of four 50-inch Leffel Samson double-horizontal turbines. Each turbine was mounted on a horizontal shaft between two single-stage double-acting Rand Drill Co. (now Ingersoll-Rand) air compressors. The complete installation had a capacity of about 16,000 c.f.m. free air, which was piped to the Chapin mine at Iron Mountain through a 24-inch riveted steel pipe 16,000 feet long. This was the longest air-transmission line in America at that time (1882). This compressor installation was dismantled in 1932 when the waterpower site was sold to the Wisconsin Michigan Power Co.

During the course of personal visits to the Victoria compressor site and talks with people familiar with early history of the upper peninsula of Michigan, the

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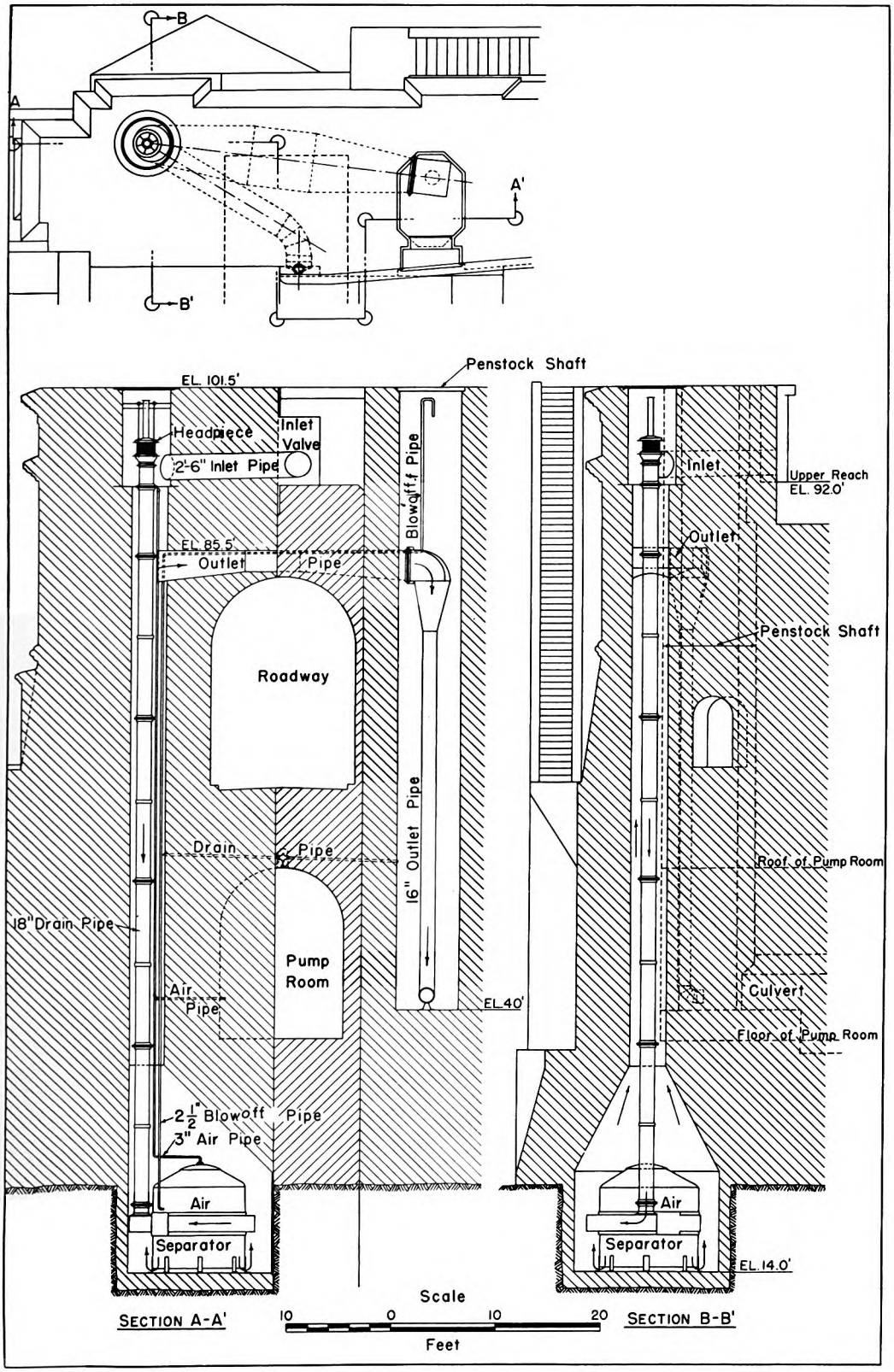

Figure 5. - Arrangement of compressor in breast wall, Trent Canal Left-Lock No. 1, Peterborough, Ontario. (From drawings supplied by Dominion Bridge Co., Montreal, Quebec.)

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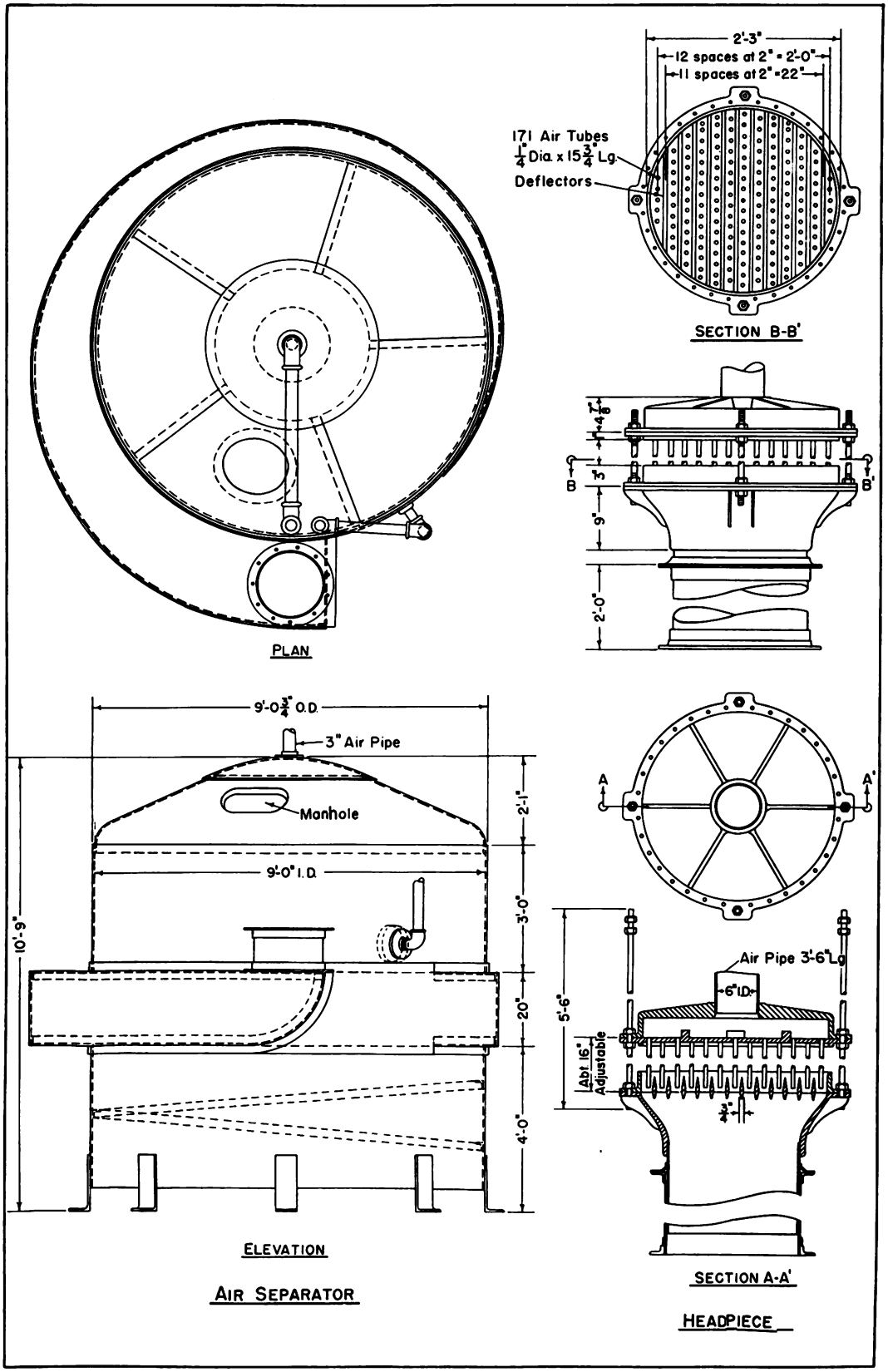

Figure 6. - Details of head piece and air separator, Trent Canal Left-Lock No. 1. (From drawings supplied by Dominion Bridge Co., Montreal, Quebec.)

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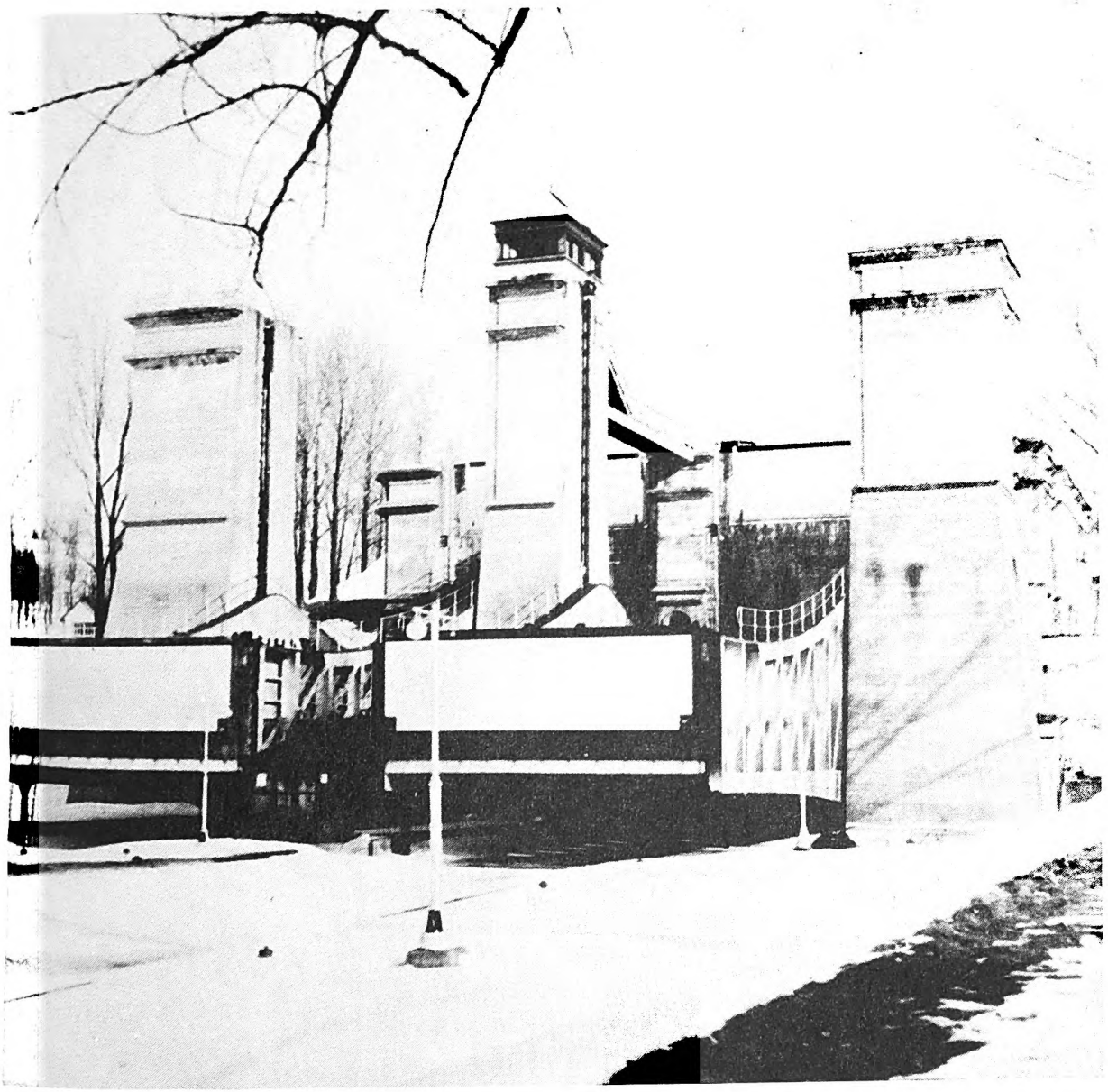

Figure 7. - Trent Canal Hydraulic Lock No. 1, Peterborough, Ontario. (Note man, lower left, at work on lift chambers, positioned at mid-point for winter.)

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Figure 8. - View showing Victoria Dam built in 1930 for hydroelectric power, original canal to air compressor under water since 1930, and plume of the compressor's safety blowoff, Victoria Mining Co., near Rockland, Mich. (Courtesy of Miss Mary M. Craig, Ontanagon, Mich., granddaughter of Mr. Thomas Hooper, Supt. of Victoria Mining Co.)

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writer assembled some interesting historical details, which make the Victoria installation part of an unusual story of copper mining. A brief condensation of references (19, 20) indicates that in about 1630 the Chippewa Indians living in the valley of the Ontonagon River led Jesuit missionaries to what they called the "copper bowlder" at a point on the north bank of the West Branch of the river about 1/2-mile above the present Victoria Dam. Over a period of years many explorers and adventurers visited the boulder, and numerous attempts were made to dislodge it and transport it out of the rugged valley. In 1770 a company was formed in London to begin mining in the high hill north of the boulder site on the assumption that other boulders would be found. The company failed in its efforts when spring thaws of 1771 caused the adit they had opened to cave. Henry Schoolcraft in 1819, Gen. Lewis Cass in 1826, and finally Douglas Houghton visited the site during his survey for the Michigan Geological Survey. Interest in the boulder attracted J. K. Paul and Julius Eldred, whose names are locally connected with stories of a personal feud over the boulder. After various efforts, the boulder was finally moved to the mouth of the Ontonagon River (now Ontonagon, Mich.) in 1843, and Eldred saw it deposited in the National Museum (Smithsonian Institute) in Washington (19).

Actual mining, at what was then called the Cushin mine, began in 1849 with reopening of a series of old pits found along the high ridge. The pits are reliably believed to be the work of early miners who used "native" or mass copper for weapons and ornaments. They may have been the people who transported the mass copper artifacts to South America where they have been found in recent years.

The Forest Mining Co. was organized in 1850 and continued the work on the Cushin site. In 1858 it was reorganized as the Victoria Mining Co. Capt. Thomas Hooper is reported to have pumped out the old workings in 1881 and, finding the timbering rotted, permitted the mine to fill again. The final and most productive work was begun in 1899, when Hooper was made superintendent by the Victoria Copper Mining Co. and began large-scale operations. He faced the problem of a source of power for expanded mining activity. Steam power was obtained by burning wood out on the mine property, then later coal was hauled by team some 4-1/2 miles from Rockland siding over a tortuous route having grades up to 26 percent. A round trip, taking copper ore to Rockland and returning with coal, required 2 days, with the cost of hauling the coal running to $5.50 per ton (16a). The railroad at Rockland did not consider it feasible to build a spur to Victoria because of the impossible grades, and the winding route it would have to follow owing to the gorge of the Ontonagon River and its branches. The river was about 300 feet below the mine location. Hooper studied the problem and secured approval to begin constructing a power dam. A general panorama view (fig. 8) shows the Hooper dam on the right, the winding canal, which followed the north bank of the river, and the new (1930) Victoria Dam then being completed. The storage pond back of the Victoria Dam has covered the Hooper dam and canal. Hooper began work in 1902 at a point about 1/2 mile above Glenn Falls, to impound the water of the Ontonagon River. The dam was 600 feet long and 24 feet high and included six 6- by 7-foot gates. A canal 20 feet wide and 17 feet deep was constructed along the north bank of the river for a total of 4,700 feet to the point where the water was to be used. During 1903 Hooper visited Norwich, Conn., to inspect the Taylor-type compressor there, and old letters attest the fact that a lively controversy developed between Taylor and Webber as to which one held controlling patent rights needed in the proposed Victoria compressor. Taylor apparently won out and closed a contract with Hooper in July 1903 for design of the air compressor with a capacity of 4,000 hp. and guaranteed to operate at an efficiency of 70 percent or better. Taylor agreed to accept $1,000 less than the contract price for each 3 percent the efficiency fell below 70 percent.

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Reporting to the stockholders for 1904, Hooper (16b) lists the various activities, in addition to the usual mining work, related to the construction of the hydraulic air compressor. One easily recognizes the phenomenal amount of physical work done by the men of those days, working under severe handicaps. In 1904 Taylor, in charge of the design and construction, drilled 3 center holes, each 5 inches in diameter, to a depth of 315 feet vertically as a location centerline for the three 5-foot-diameter intake shafts to follow. An inclined shaft, 16 by 18 feet in section, was cut through solid rock at an angle of 70° with the horizontal a distance of 308 feet on the incline for the discharge water. This shaft was equipped with a skip hoist and sump pumps. At the bottom of the shaft, a tunnel was driven horizontally toward the intake shaft centerline holes 130 feet from the inclined shaft. A discharge outlet connecting to the river channel was cut through rock, and a dry-wall and breakwater were constructed. The river bottom below the outlet was cleared of all large boulders and debris for 1,000 feet. All of this work was done by hand with the help of horses and some steampower on skip hoists. In addition, Hooper reported completion of a water tunnel 325 feet long running from the forebay of the compressor intake to the stamp-mill location to supply water to the mill, and the laying of a 14-inch main airpipe from the hydraulic plant site to the mine, 4,300 feet. This pipe was laid in a trench below frostline, which had to be excavated mostly out of solid rock.

During 1905 little work was done at the mine, as all available labor was concentrated on construction of the air compressor so as to secure airpower for the mine and for operation of the pneumatic stamps. The three 5-foot-diameter intake shafts were sunk 316 feet to connect with the tunnel, which in turn connected with the inclined discharge shaft. The tunnel was enlarged into an air-separator chamber having a cross section of 18 by 21 feet and a length of 281 feet. The 12-inch blowoff pipe and the 24-inch air main were placed in the inclined shaft and concreted in place and run up to the surface to a regulator building where the 24-inch main connected with the 14-inch main already in place. A total of 6,000 cubic yards of rock was removed that year from the intake shafts and the air-separator chamber. Other jobs completed that year included construction of a stamp-mill building 50 feet by 150 feet (fig. 9) to house concrete rock bins, stamp heads, jigs, and tables (figs. 10 and 11). One Cuyahoga stamp head, 28 jigs, and 1 Wilfley slime table were installed. A new mine hoist house measuring 38 feet by 40 feet was built on stone foundations and a Webster, Camp, & Lane hoist was installed. A shaft house 37 feet by 40 feet with rock bins holding 500 tons was erected. A gravity railroad from the shaft house to the stamp mill, about 4,800 feet including 1,000 feet of trestle construction and requiring 6,000 cubic yards of earth to be moved for grading was finished. Snowfall begins in October in this part of Michigan and continues through a long winter running well into March and later, so progress such as the above is significant.

Thomas Hooper retired in 1906, and his son, George Hooper, continued as superintendent. The three 5-foot-diameter intake shafts, 320 feet deep, were completely concreted, the heavy cast-iron intake heads with their complex fittings were installed, and a steel-frame building 20 by 60 by 24 feet high was erected over the intake equipment. After all timbering, skip hoists, and pumps from the shafts and chambers were cleared out, the gates at the dam were opened on March 9, 1906, and the compressor was placed in operation.

Because of Taylor's efficiency guarantee, the compressor was tested May 28 and 29, 1906, by Prof. Sperr and Prof. Hood of the Michigan College of Mining, Houghton, Mich. Their report follows:

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Figure 9. - Stamp-mill building, Victoria Mining Co. (Courtesy of Miss Mary M. Craig.)

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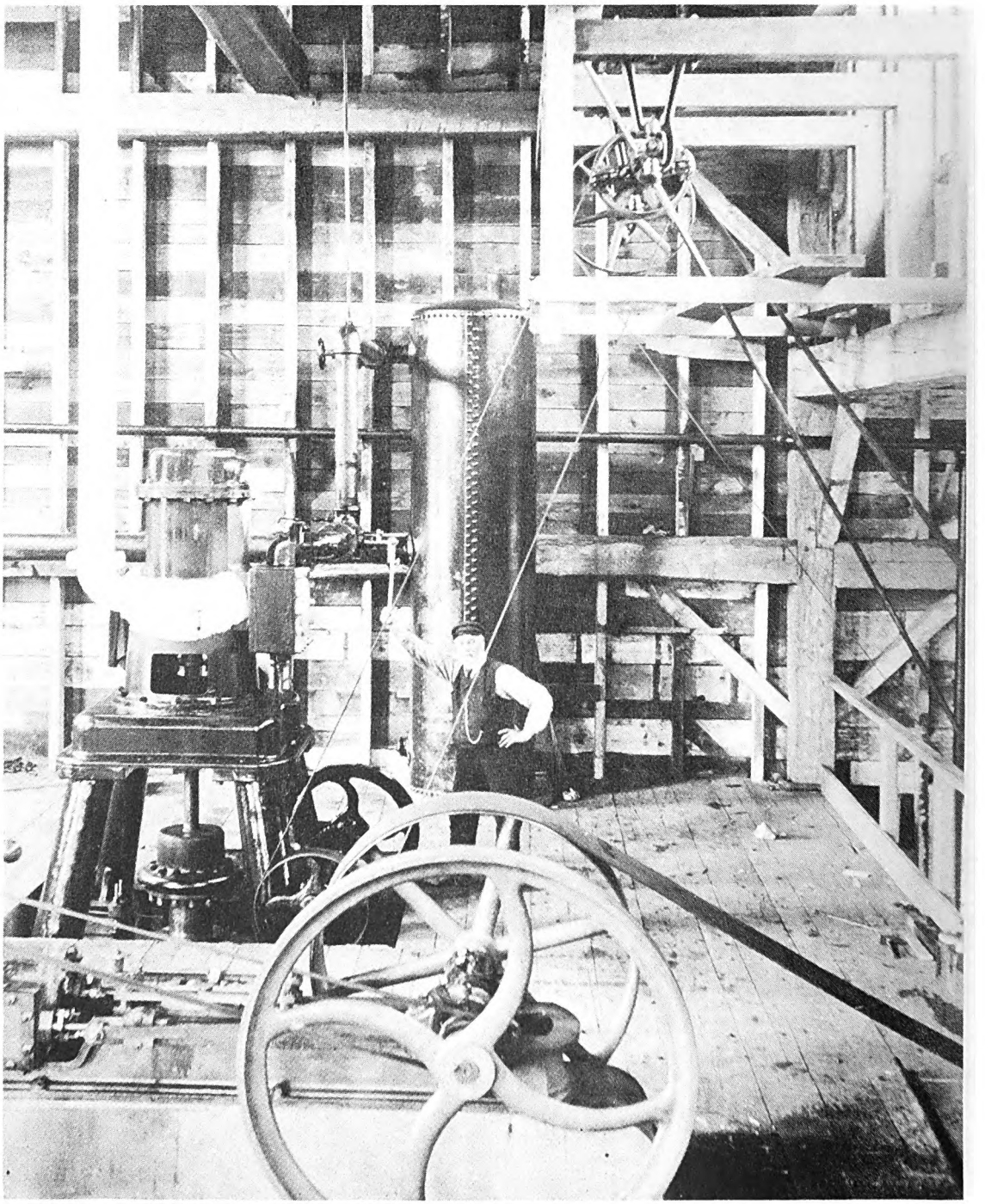

Figure 10. - Air-operated stamp head, Victoria Mining Co.
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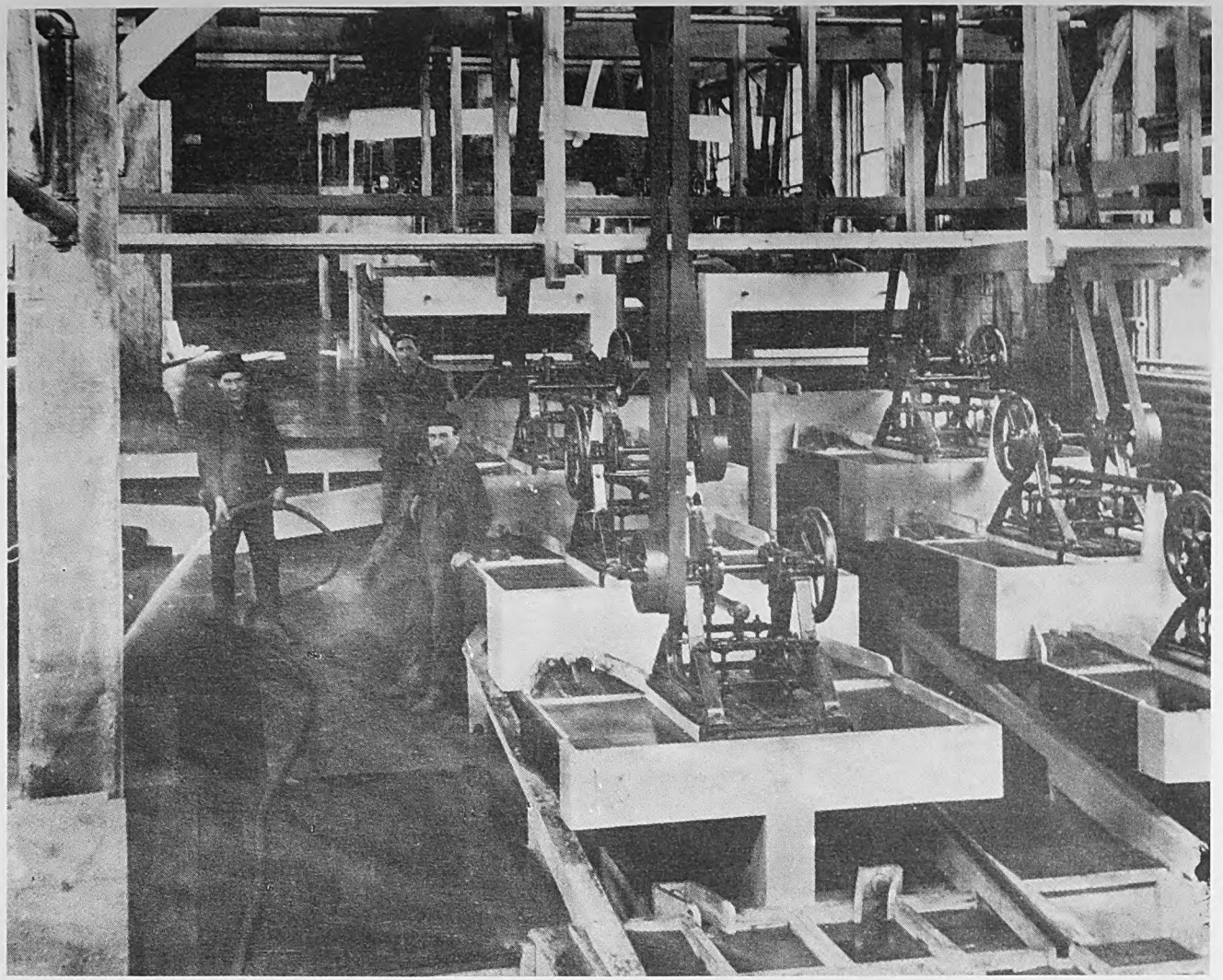

Figure 11. - Jigs, Victoria Mining Co. (Courtesy of Miss Mary M. Craig.)

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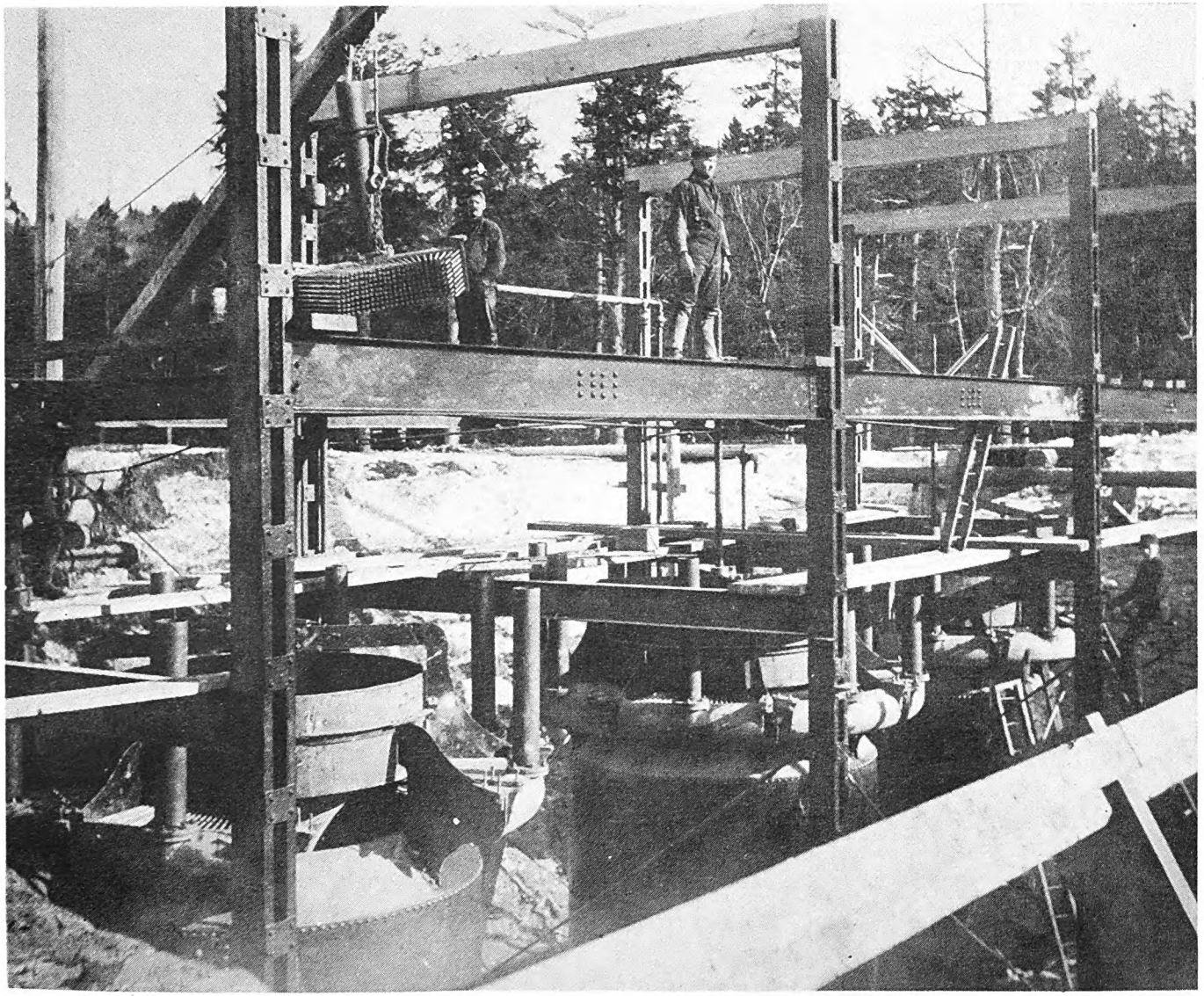

Figure 12. - Intake heads, Victoria Mining Co. Note a section of air tubes ready to be lowered. (Courtesy of Chas. H. Taylor (deceased), Toronto, Canada.)

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Houghton, Michigan, June 9, 1906

Captain Thomas Hooper,
Superintendent Victoria Mine,
Victoria, Mich.

Dear Sir:

In accordance with your request of the 9th of May, observations have been made to determine the efficiency of the Taylor Hydraulic Air Compressor installed at the Victoria Mine.

Three similar heads have been installed and measurements were made of the air and water supplied to the middle head, the other two not running. The head to be tested was enclosed in a tight chamber and the velocity of the air, admitted through a duct two feet square, was measured by an anemometer. Within the canal leading to the penstock a flume was placed approximately 70 square feet sectional area, and water velocities across the whole section were determined by a current meter. The observations were taken May 28 and 29 by Professor F. W. Sperr. The results of three tests are as follows:

AIR MEASUREMENTS

Sq. ft.	Vel. per second	Cu. ft. per minute	Absolute-pressure Free	Com.	Horsepower
4	44.09	10,580	14	128	1430
4	49.74	11,930	14	128	1623
4	38.50	9,238	14	128	1248

WATER MEASUREMENTS

Flume area	Vel. per second	Cu. ft. per minute	Head, ft.	Horsepower	Efficiency
71.75	3.033	13,057	70.5	1741	82.17%
67.03	3.684	14,820	70.0	1961	82.27%
72.16	2.936	12,710	70.6	1700	73.50%

Two tests at near the maximum capacity show the exceptionally high efficiency of 82%. The separation of the air from the water seems to be completed.

Respectfully submitted,
F. W. Sperr,
O. P. Hood.

About $10,322 worth of copper was produced and sold in 1904, but none in 1905 as all labor was required for compressor construction. When the stamp mill and air-compressor went into operation in 1906, 546,334 pounds of fine copper was sold for $114,870, resulting in the first profit of $34,829 for the year. During 1907, 2,062,210 pounds of ore was mined, which yielded 1,207,337 pounds of copper and sold for $343,597 to net a profit of $48,666 for the year. A serious drought during the fall of 1908, with resultant lack of compressed air, cut ore production badly. In

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1909 the J. G. White & Co. engineers studied and made recommendations for development of additional water storage. Demand for copper fell in 1909, and a serious loss was sustained. Another dry fall in 1910 resulted in the air compressor operating only part time from August to January. Losses were sustained in each year from 1910 through 1913. The spurt in copper demand due to war in 1914 changed the situation, and ambitious plans by the company engineers for construction of a second hydraulic air compressor at a point downriver from the existing one were considered. A Nordberg hoist was installed to serve a second shaft. Operation was begun in 1916. Copper demand again declined after termination of World War I, and finally in the summer of 1921 management ordered operation to stop completely. Little copper mining was done in the entire Michigan area during the years from 1921 to 1929, when the powersite was purchased by a development group and the Victoria Dam of the Copper District Power Co. was built. The Taylor compressor was sufficiently reconditioned to supply all the air needed during construction of the dam and powerhouse.

Many early problems were encountered in operating the hydraulic air compressor. The severity of the winters in the upper peninsula of Michigan usually cause "frazil" ice to form in the flowing river water. This crystal ice was carried into the canal and to the intake heads of the compressor, where it lodged between the rows of 3/8-inch-diameter air tubes. It seemed impossible to keep this ice formation out of the intakes, and it was necessary to remove the entire "bustle-pipe" (a name coined by the technical writers of that day to apply to the annular-ring pipe with its hundreds of small air tubes, which extended horizontally into the flowing water as it passed over the lip of the intake head) assembly (a section of which is shown in fig. 12 ready to lower into place during erection in 1905). The water then flowed freely over the lip of the cast-iron headpiece, and no serious plugging resulted from frazil ice. Although not tested, it was reported that little decrease in quantity of air compressed was noticed. Frizell (8) questioned the necessity for using small air-tubes and contended that his design, with wide-open inlet, would allow debris to pass through. He did not mention what would happen if the floating debris accumulated in the upper part of the air-separator chamber. Taylor in his later design for the Cobalt installation eliminated the small air tubes.

Another problem had to do with the automatic, floating, headpiece. Taylor's original design, shown in figure 12 and in the reproduction of one of his drawings (fig. 13) had a steel-plate skirt riveted to the rim of the cast-iron intake head. This was to create buoyancy, which, it was planned, would permit automatic raising and lowering of the entire intake unit whenever air was admitted under the skirt or vented from it. The telescopic fit of this headpiece into the fixed sleeve of the downfall shaft caused trouble because of distortion, dirt, and rust and did not permit freedom of movement suitable for easy control. Possibly this was for the best, because one of the dangers of operating this compressor is in too rapid shutting off of the waterflow. This will be discussed later in more detail.

The steel-plate skirts were removed, and the flow of water over the lip of the intake head was controlled manually by means of the running thread and capstan nut, figure 14.

A winter operation problem encountered at Victoria related to the formation of a large iceberg built up by discharge from the blowoff pipe (fig. 15). During severe weather, this accumulation of ice had to be dynamited to prevent plugging of the flow from the blowoff. It appears that freezeup of the blowoff was the reason for one of the destructive blowbacks, which occurred when the compressor was left to deteriorate following its use in 1930.

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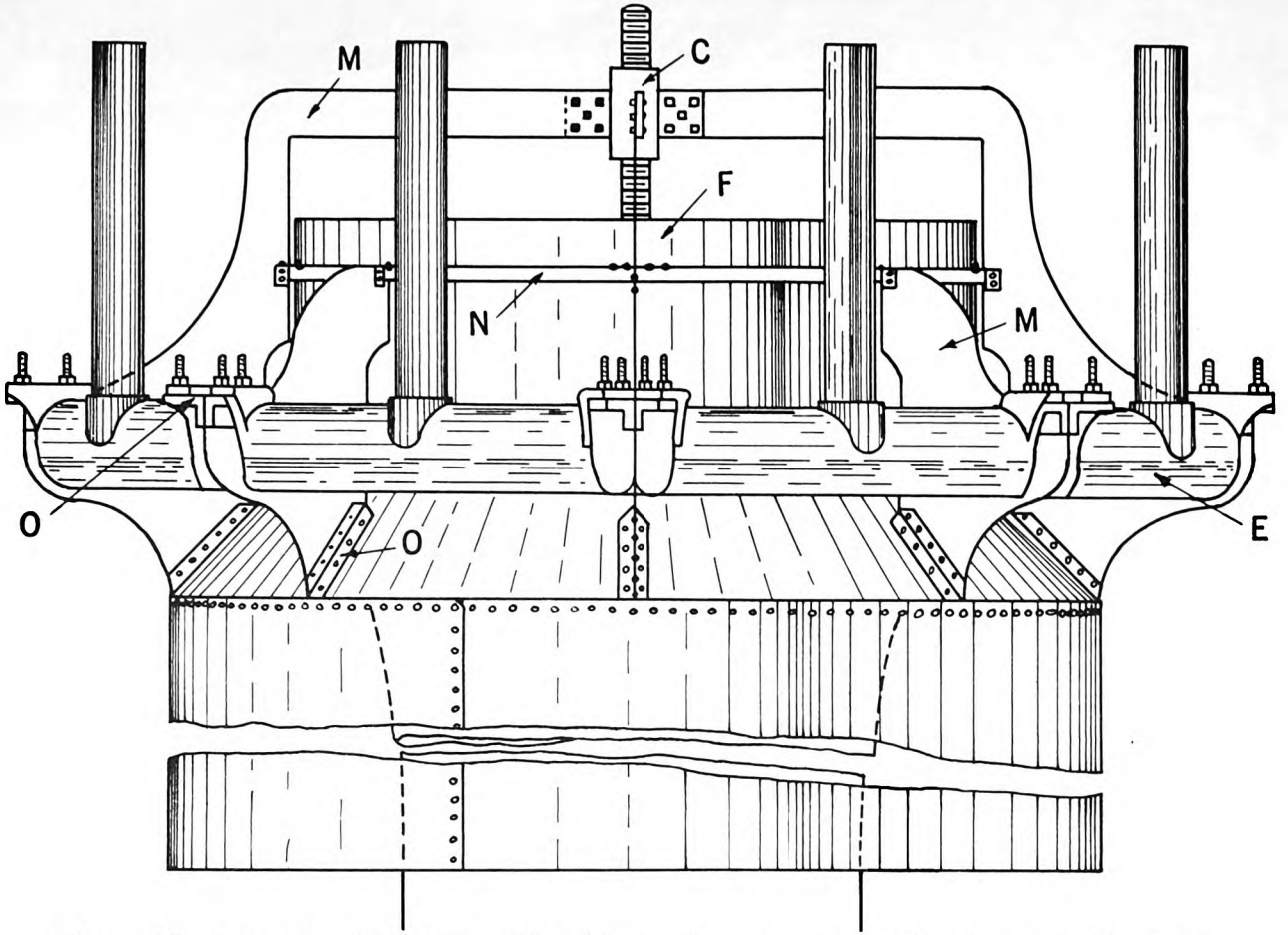

Figure 13. - Drawing of assembly of headpiece, showing sectional bustle pipe with air-inlet pipes, Victoria Mining Co. (Reproduced from an old photographic glass negative of drawing by Chas. H. Taylor in 1904. Courtesy of Mr. Taylor (deceased), Toronto, Canada.)

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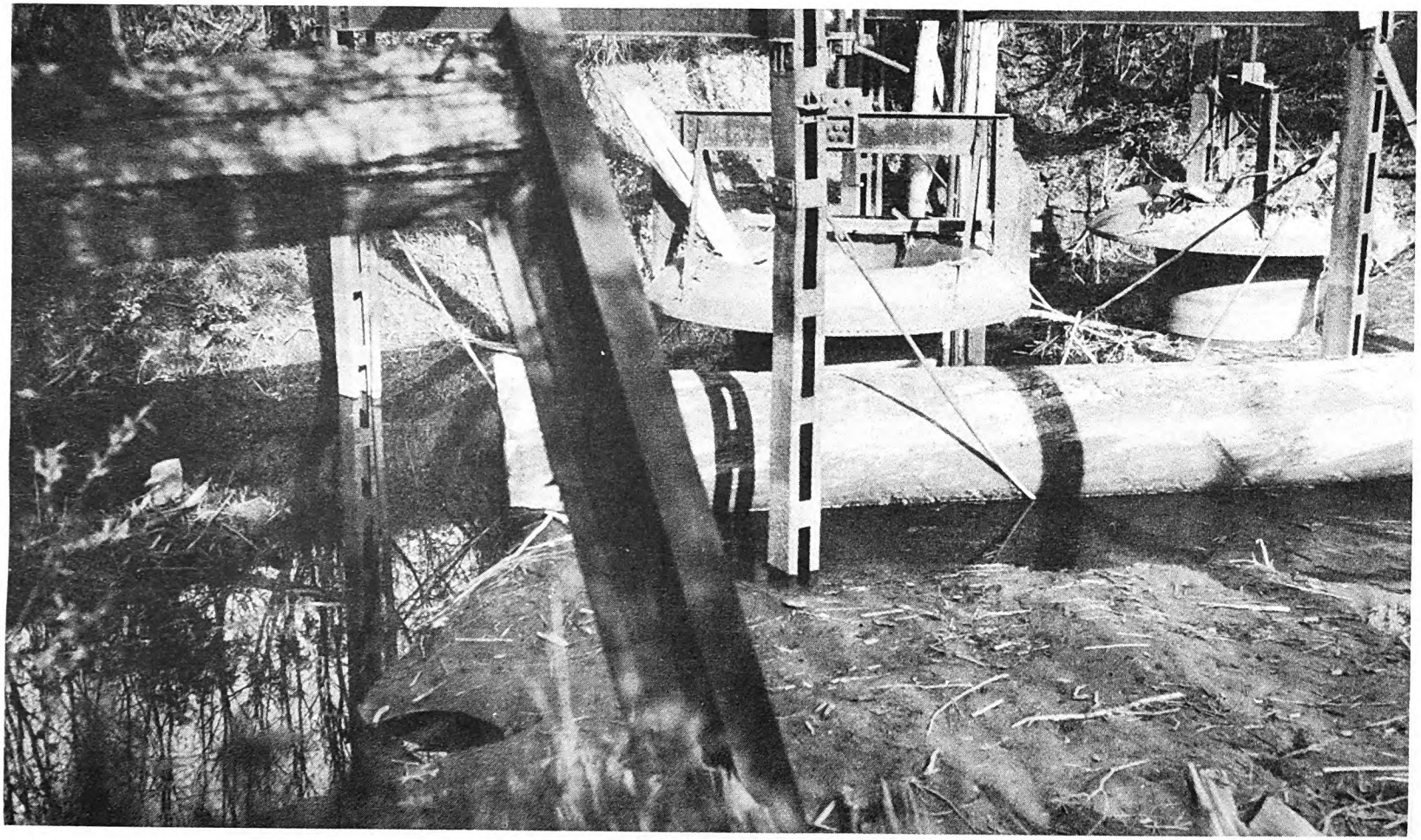

Figure 14. - Condition of intake heads in 1949, Victoria Mining Co. (Courtesy of Miss Mary M. Craig.)

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Figure 15. - Ice tower formed by discharge of air and water from safety blowoff during winter, Victoria Mining Co. (Courtesy of Miss Mary M. Craig.)

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Figure 16. - How a blowback wrecked intake building, Victoria Mining Co., about 1914. (Courtesy of Miss Mary M. Craig.)

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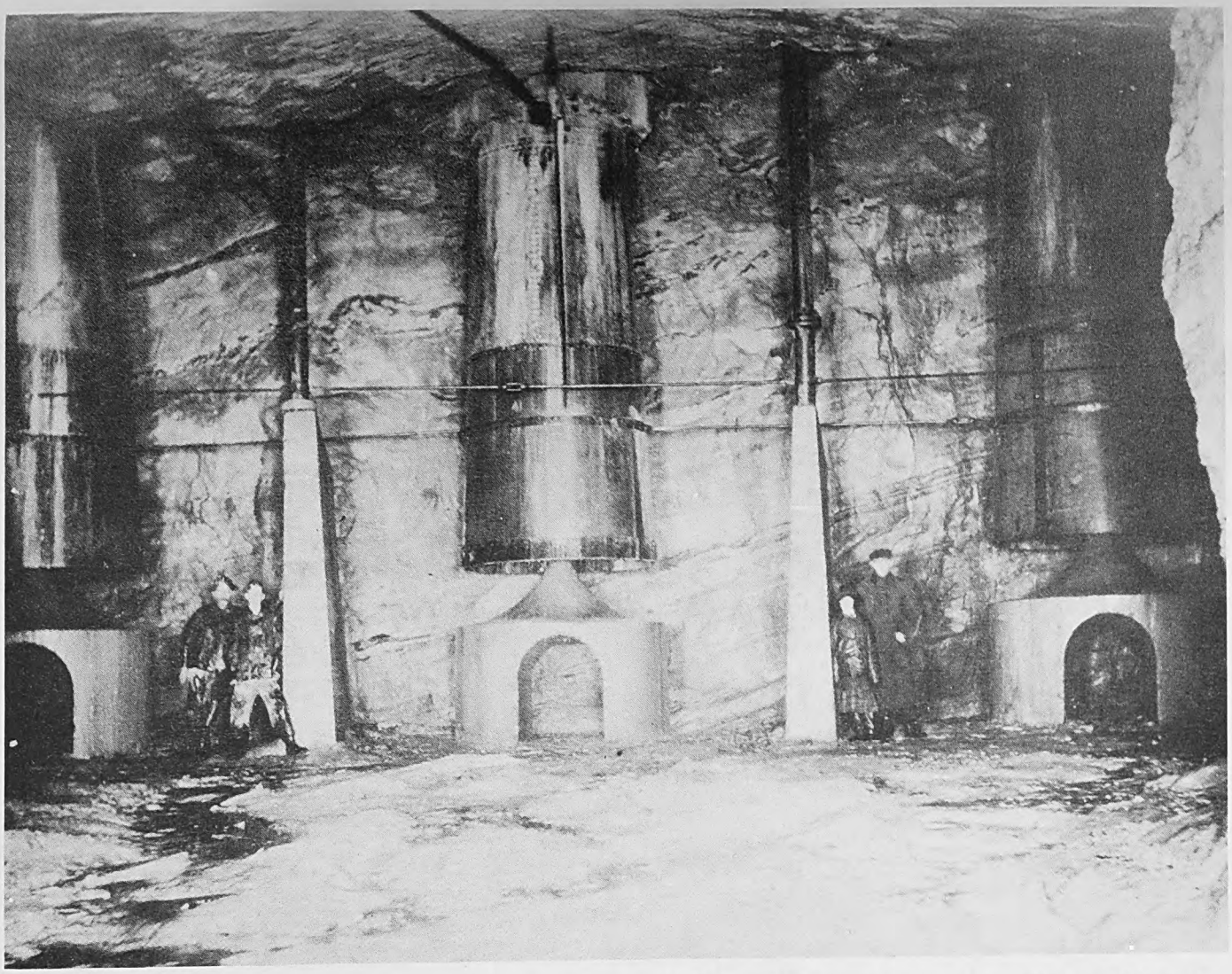

Figure 17. - Interior of air chamber, showing three steel tubes at bottom of fall shafts, Victoria Mining Co.'s compressor, taken by Mr. Taylor prior to placing compressor in operation in 1906. (Courtesy of Mr. Chas. H. Taylor (deceased), Toronto, Canada.)

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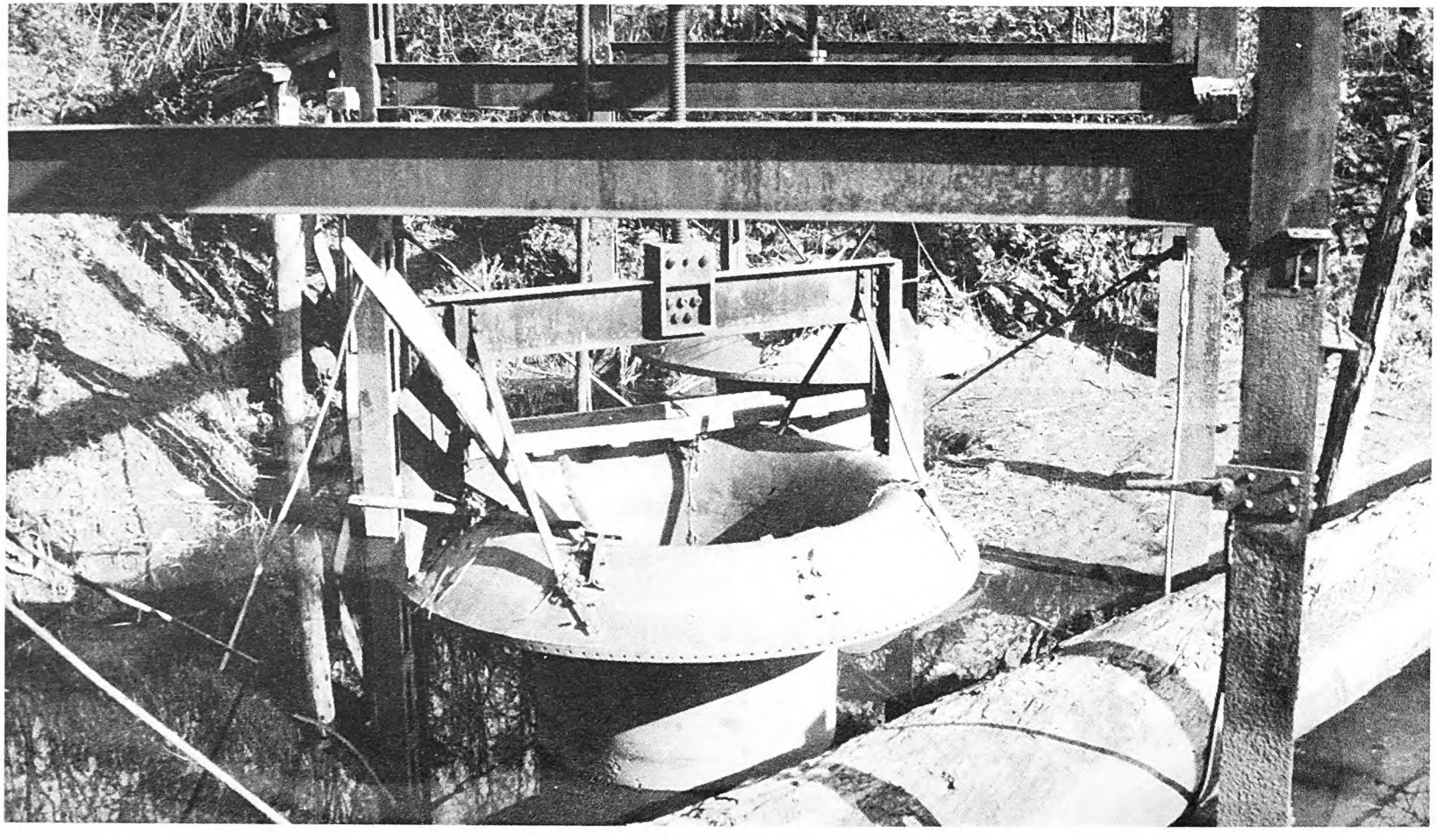

Figure 18. - Condition of intake heads, Victoria Mining Co., 1949, showing two cast-iron head pieces still in place. Bustle pipe fitting and skirt were removed years ago and headpiece was operated by hand by means of running thread and capstan nut.

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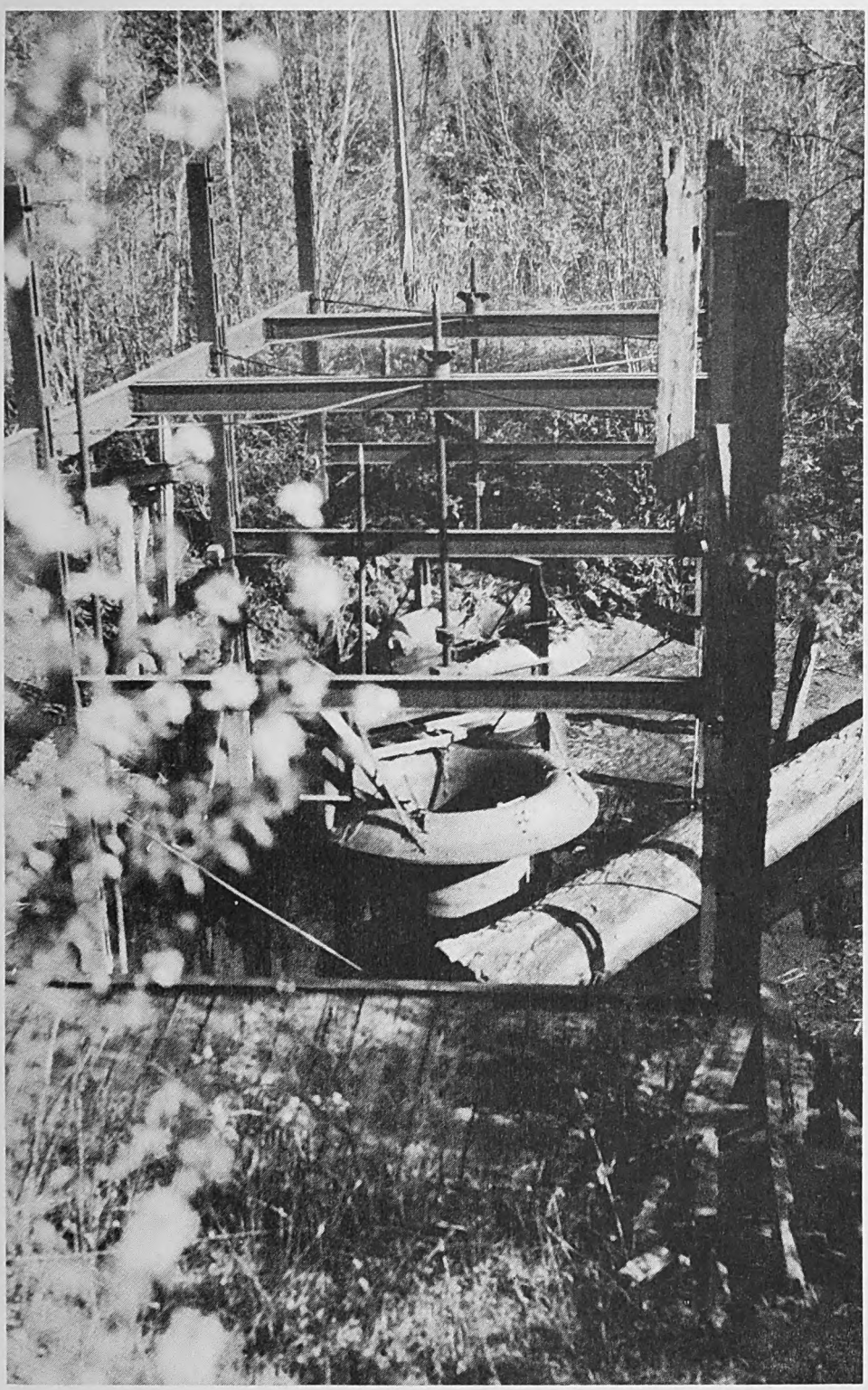

Figure 19. - Condition of the steel supporting frame, Victoria Mining Co., 1949, No. 1 intake head blown through building took out some of the steel members. Intake head casting embedded in earth about 50 feet east of building, was never replaced after last blowback.

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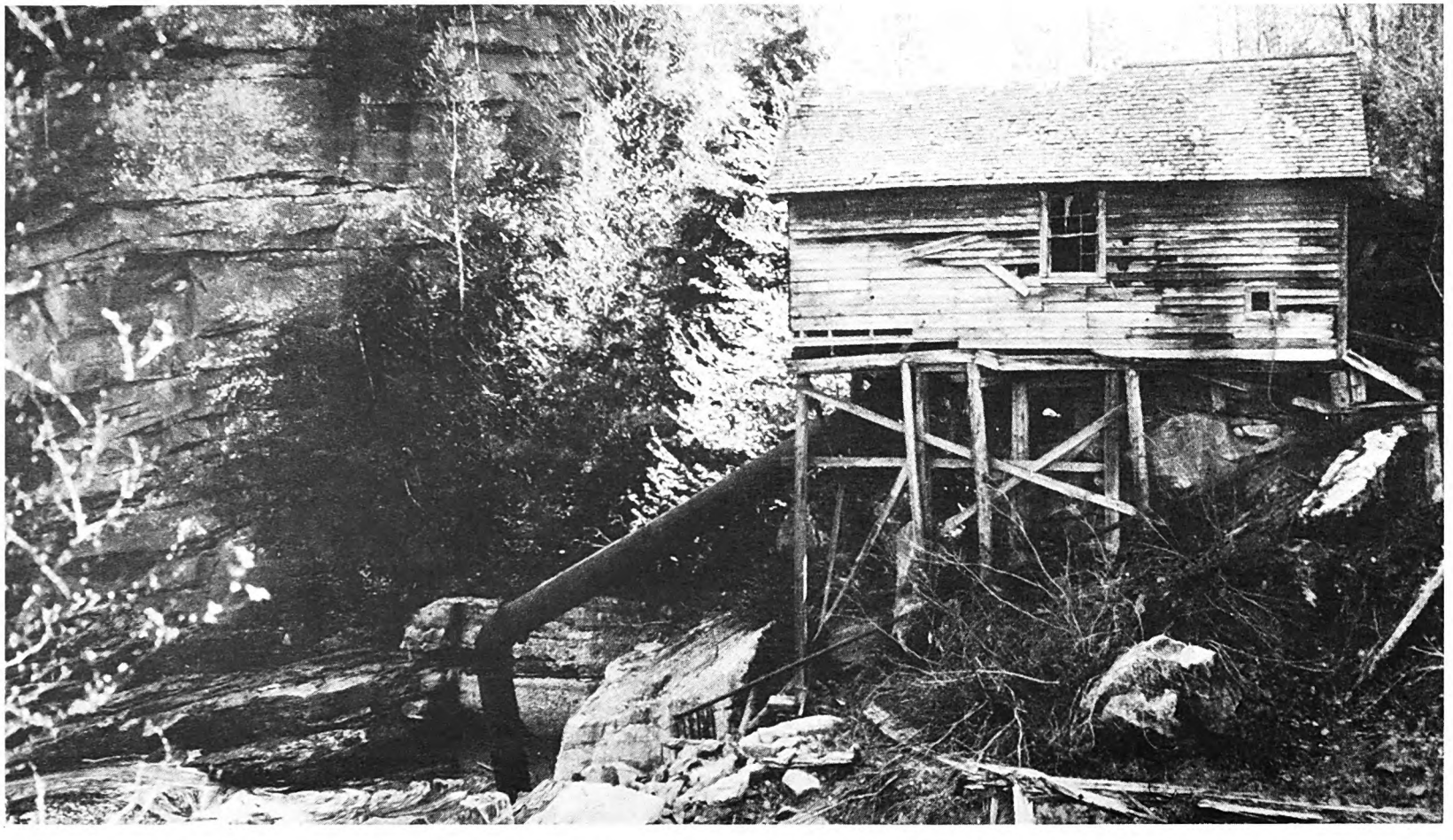

Figure 20. - Condition of the discharge opening, Victoria Mining Co., 1949, 24-inch air main to regulator building, 12-inch blowoff pipe taken out by ice in recent years.

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Figure 21. - View of blowoff geyser from the 12-inch safety blowoff pipe, Victoria Mining Co. (Courtesy of Miss Mary M. Craig.)

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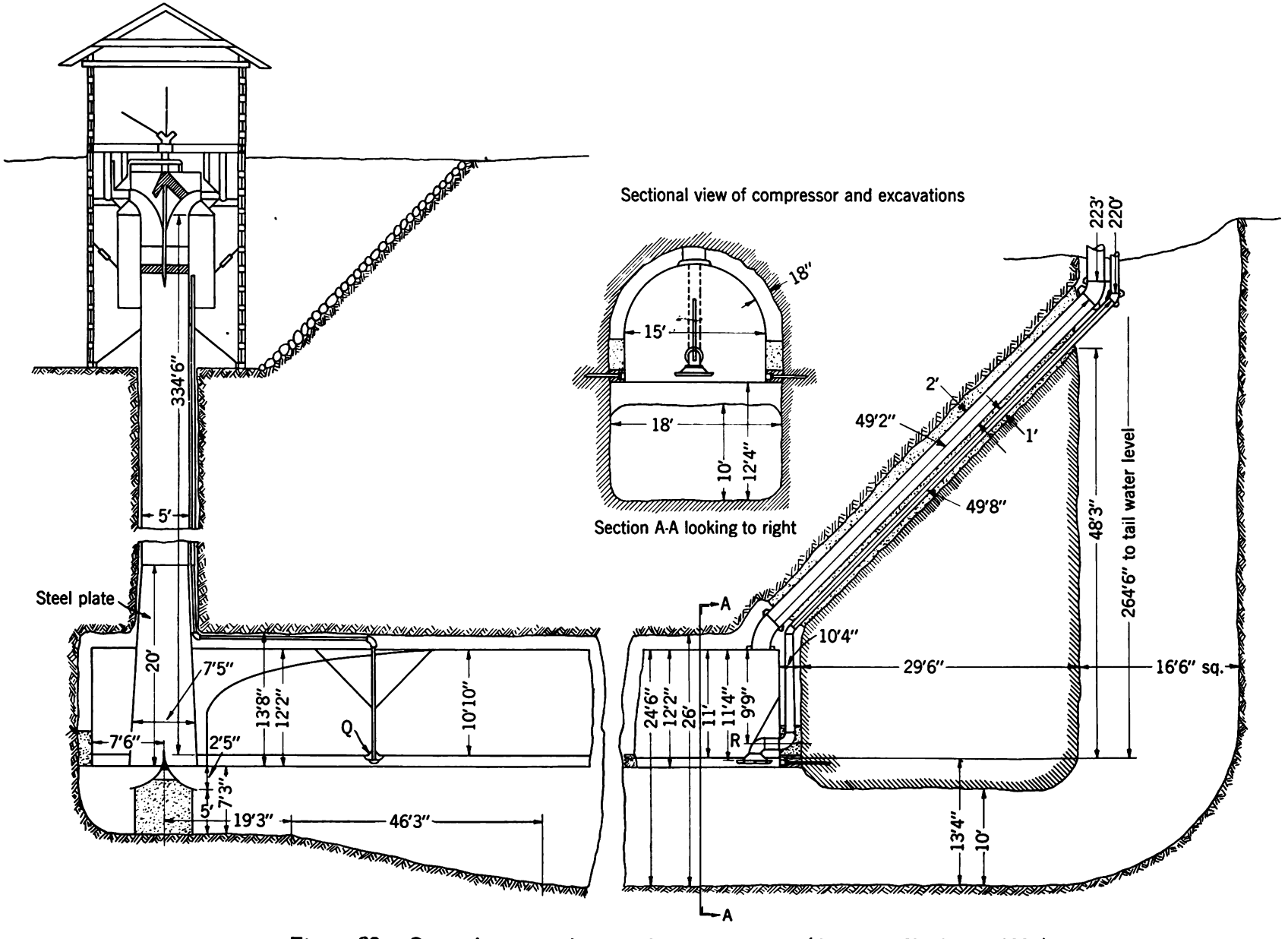

Figure 22. - General sectional view of air compressor (drawn by Taylor in 1903).

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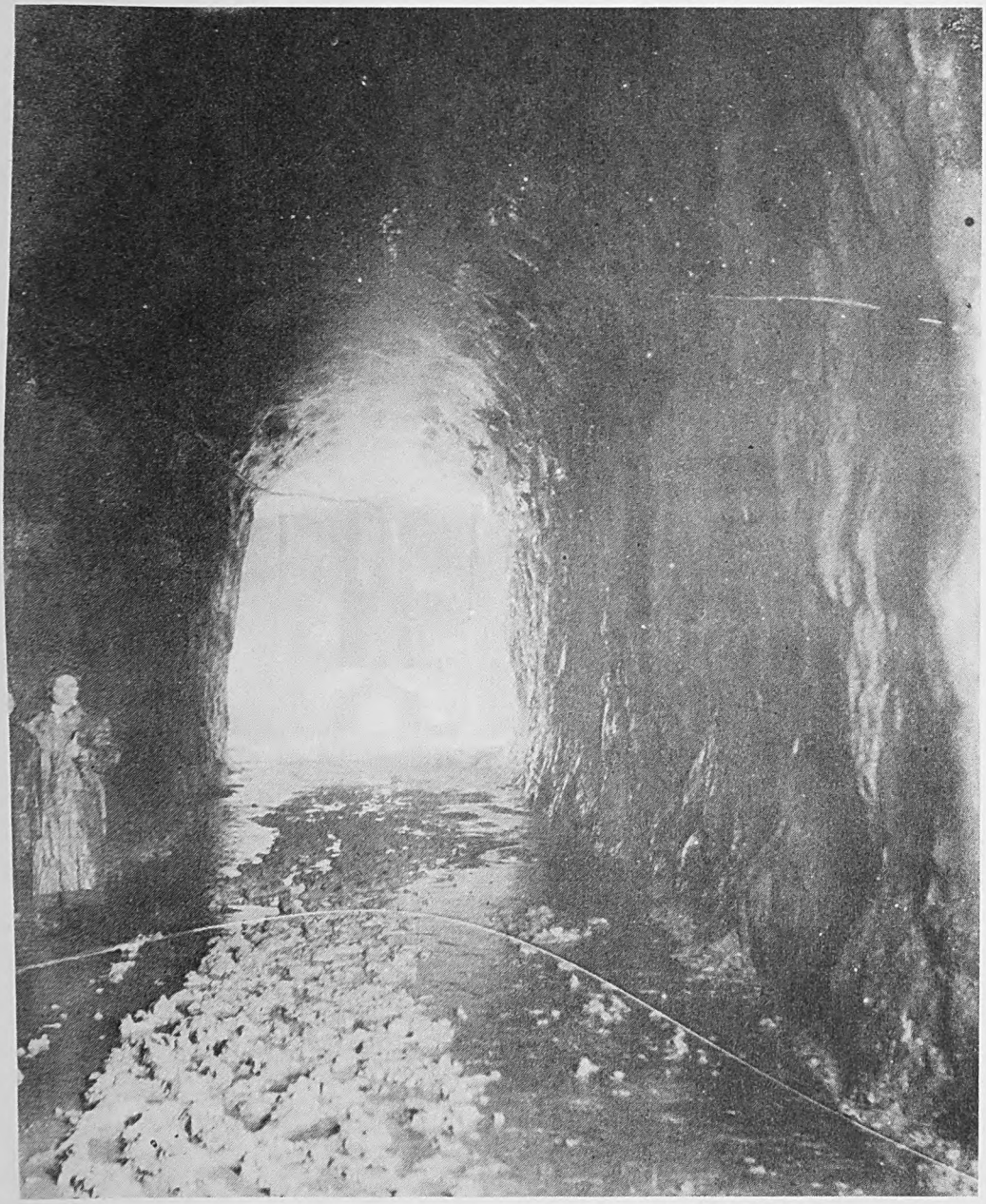

Figure 23. - View of interior of air-separating chamber looking toward inlet, taken in 1906 just before placing compressor in operation, Victoria Mining Co. (Courtesy of Chas. H. Taylor (deceased), Toronto, Canada.)

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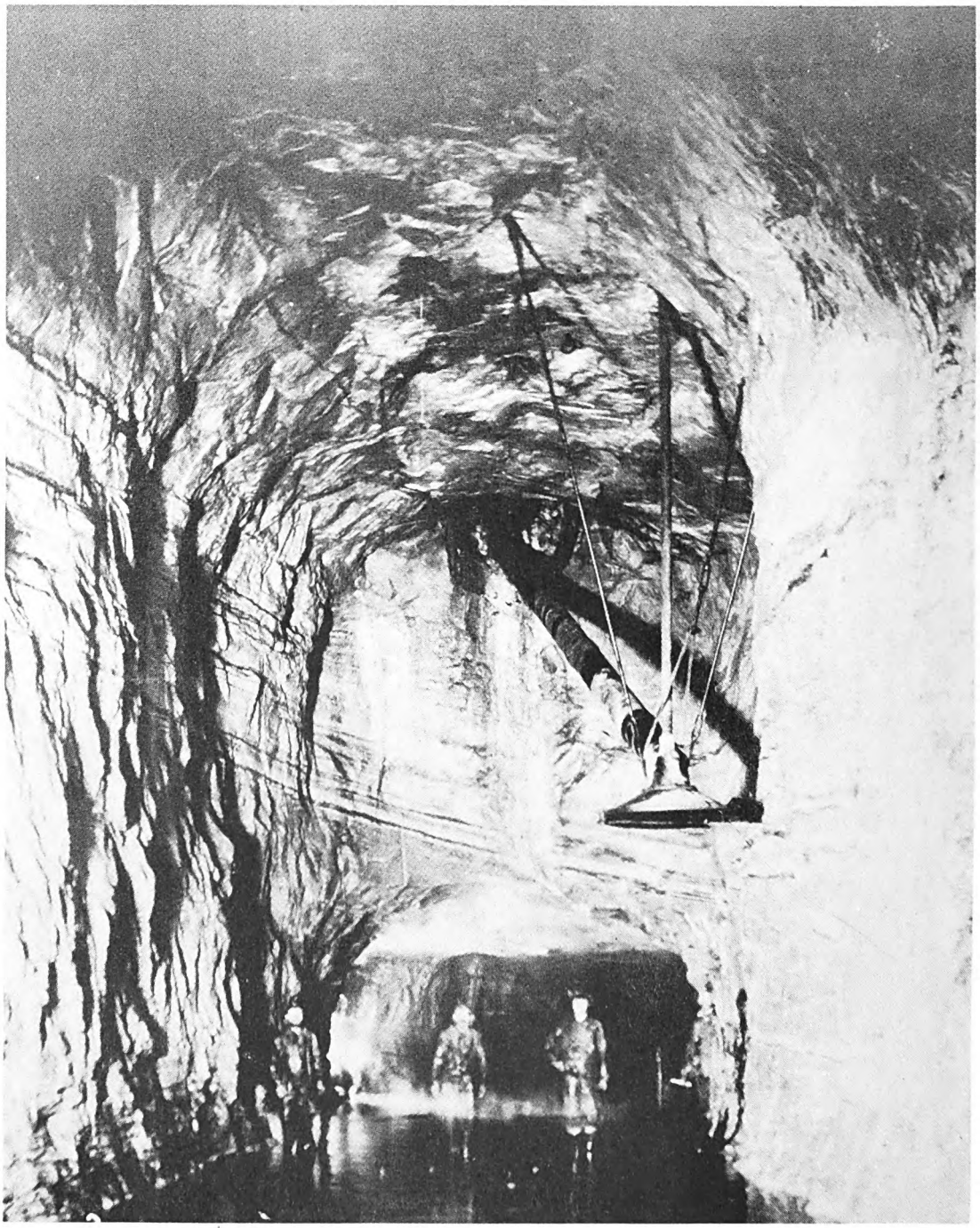

Figure 24. - View of interior of air-separating chamber looking toward discharge end before compressor operation, Victoria Mining Co., 1906. (Courtesy of Chas. H. Taylor (deceased), Toronto, Canada.)

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The explosive blowback, which occurred on several occasions at Victoria and at least on one occasion at Cobalt, was not publicized. According to former employees of the mining company who worked on the compressor, it was believed that the first blowback occurred sometime between 1914 and 1916. Owing to decreased flow available to the compressor, it was decided to reduce the 5-foot diameter of the No. 2 (center shaft) intake by casting a concrete collar inside the headpiece. It is reported that a sudden explosion of air and water up the No. 1 intake, due to an error in stopping the flow of the operating headpiece too quickly, wrecked it and caused the steel frame of the building to bend as well as demolishing a portion of the building, as shown in figure 16. On another occasion, perhaps during the winter of 1920, after the mine had been shut down, considerable ice accumulated on the safety blowoff, preventing relief of the air chamber. Before this could be removed, the water level in the air chamber had lowered to a point where it uncovered the lower end of the steel tubes (fig. 17). Probably because No. 1 intake (on the right in fig. 17) was the one that had been in use, it was this one up which the high-pressure air and water rushed. The force of the explosion of water and air hurled the 5-ton cast-iron intake piece through the building to the outside. Again in the winter of 1934, owing to freezing of the blowoff pipe, blowback occurred, and the building was never repaired. Figures 18, 19, and 20 show the present condition of the intake and the outlet and regulator valve building. The intermittent operation of the blowoff, which continued for many years as a tourist attraction, is shown in figure 21.

Figure 22 is a photocopy drawing of the general plan made by Taylor in 1903. It is noted that he contemplated arrangement of a large timber around the air chamber at about the water level at maximum storage capacity. This timber would serve as a support for a concrete seal and also for attachment of the steel liner of the chamber above water level. By comparing this drawing (fig. 22) with the three flashlight photographs (figs. 17, 23, and 24) taken just before the compressor went into operation in 1906, it is noted that the steel lining was omitted. During construction it was found that the sandstone in which the chamber was built was so nearly without cracks that it seemed practical to leave out the steel liner. Whereas this was an economy in original construction, it is known that, when the chamber was under pressure, air was continually leaking away and could be heard at the surface and seen rising through still water in the area above the storage chamber. This was particularly noticeable during the last years of operation in 1929 and 1930.

As a result of his experience and design changes at Victoria, Taylor applied for a United States patent on various features that were a part of the Victoria compressor design. Patent 892,772, issued on July 7, 1908, shows details of the automatic, floating headpiece and other features. As pointed out above, the floating headpiece was found impractical at Victoria, at least in the form used by Taylor.

The large air-storage capacity, inherent in the air-separator chamber design used by Taylor, is a feature of this type of compressor, which merits more consideration in any present-day application. It is a sound engineering method of storing energy. The Victoria compressor air separator had about 80,000 cubic feet of volume, which could be drawn upon in case of emergency or for short-time excess demand for air. During the period of transition from steam-engine drive to electric-motor drive of mine hoists and air compressors, the problem of having an emergency source of power with which to hoist miners from the lower levels was a vital one. Rix comments (17) that the early installations of electric-motor drive for hoists had disadvantages owing to "outages" from mechanical faults or storms and to trouble with the starting and control equipment. Before development of satisfactory motor drive for hoists, pumps, and stamps, which had all been operated by steam or air power, the expedient sometimes followed was to install an electric-motor drive for

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the air compressor and pass the compressed air through the partly heated steam-boiler drum, pre-heating the air and reducing moisture separation in cylinders. In case of electric breakdown the steam boiler was quickly brought up to pressure and steam was used to power the hoisting equipment. Another ingenious plan was that of Nordberg (18) at Anaconda Copper Mining Co., Butte, Mont., where, by means of a bank of 16 pressure receivers and a water-storage tank above them, he obtained a stored energy of 865,000,000 foot-pounds, which was enough to operate the hoists of a number of mines served by this central air-compressor station in case of emergency.

Several of the German and Swedish hydraulic air compressors used this same method of storing energy, as will be brought out later.

Cobalt Hydraulic Power Co., Cobalt, Ontario, Installation

This installation, the last made by Taylor, was the largest in terms of water horsepower and air production. Discovery of silver in the Cobalt, Ontario, area in 1903 started a rapid growth of mining activity. Initially the small mines had individual steam boilers for power, which by 1908 numbered 158 boilers operated by 92 mining companies. That year there were 57 compressor plants having a total collective capacity of 38,000 c.f.m. free air. These mines produced 20,000,000 ounces of silver in 1908 (21c). Cobalt, 300 miles north of Toronto, had only 1 railroad, and hauling in coal was very costly. Freight was more than the original cost of the coal at the United States mines.

A number of the mine operators encouraged Taylor to plan and install a suitable compressor to handle the entire air requirement of the area. The Cobalt Hydraulic Power Co. was formed, and capital was obtained in New York to finance the construction. Before final plans were made, Webb, a consulting engineer retained by the new company, made a study of the existing air compressors in the area to estimate the possible saving that the hydraulic compressor plant could make over existing steam-driven compressors (21a, 21d). It is reported that the entire project cost $1,000,000 to $1,250,000 before it was finished and placed in successful operation in 1911.

Nine miles south of Cobalt the Montreal River flowed through a rugged gorge known as Ragged Chutes. Construction of a dam and compressor intake at the entrance of this gorge, with discharge from the compressor about 1,000 feet farther downstream, developed a head of 54 feet. The design was based on 5,500 hp. with 40,000 c.f.m. free air to be compressed to 120 p.s.i.g. Taylor wrote an article (21b) in 1910, which gives details of the construction then under way and nearing completion. He eliminated the multitude of small air pipes, which he had used at Victoria, and designed a double intake head. Each headpiece was in the shape of a funnel with a diameter of 16 feet at the top, decreasing to 8 feet 4-1/2 inches where it entered the shaft liner, which had a diameter of 8 feet 6 inches. Riveted on the top of the funnel was a flat tube sheet, to which 66 pipes, each 14 inches in diameter, were attached. The top ends of these 14-inch pipes were left plain (fig. 25), and the water simply flowed into the pipes and entrained as much air as possible, with no special mixing arrangement. The intake in operation is shown in figure 26.

Taylor designed 24-inch-diameter pneumatic lifting cylinders, 2 for each intake head, which would automatically raise each head with excess air production, and lower with increased demand for air. In retrospect it now appears that these air-operated cylinders may have caused the explosive blowback that occurred in the fall of 1910 (21f) when the compressor had just begun to supply the air requirements.

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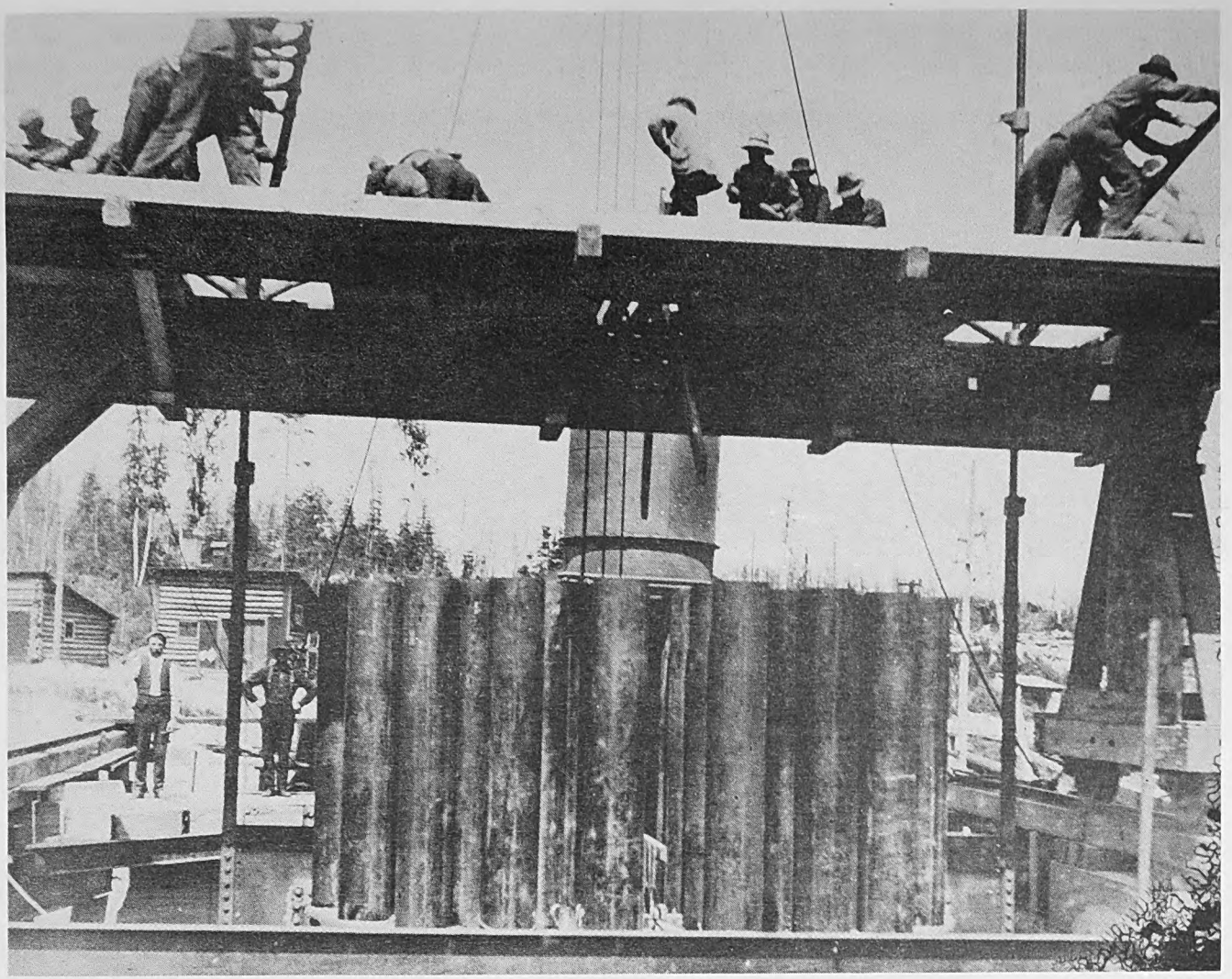

Figure 25. - Cobalt Hydraulic Power Co. compressor intake head being lowered during construction in 1910. (Courtesy of Chas. H. Taylor (deceased), Toronto, Canada.)

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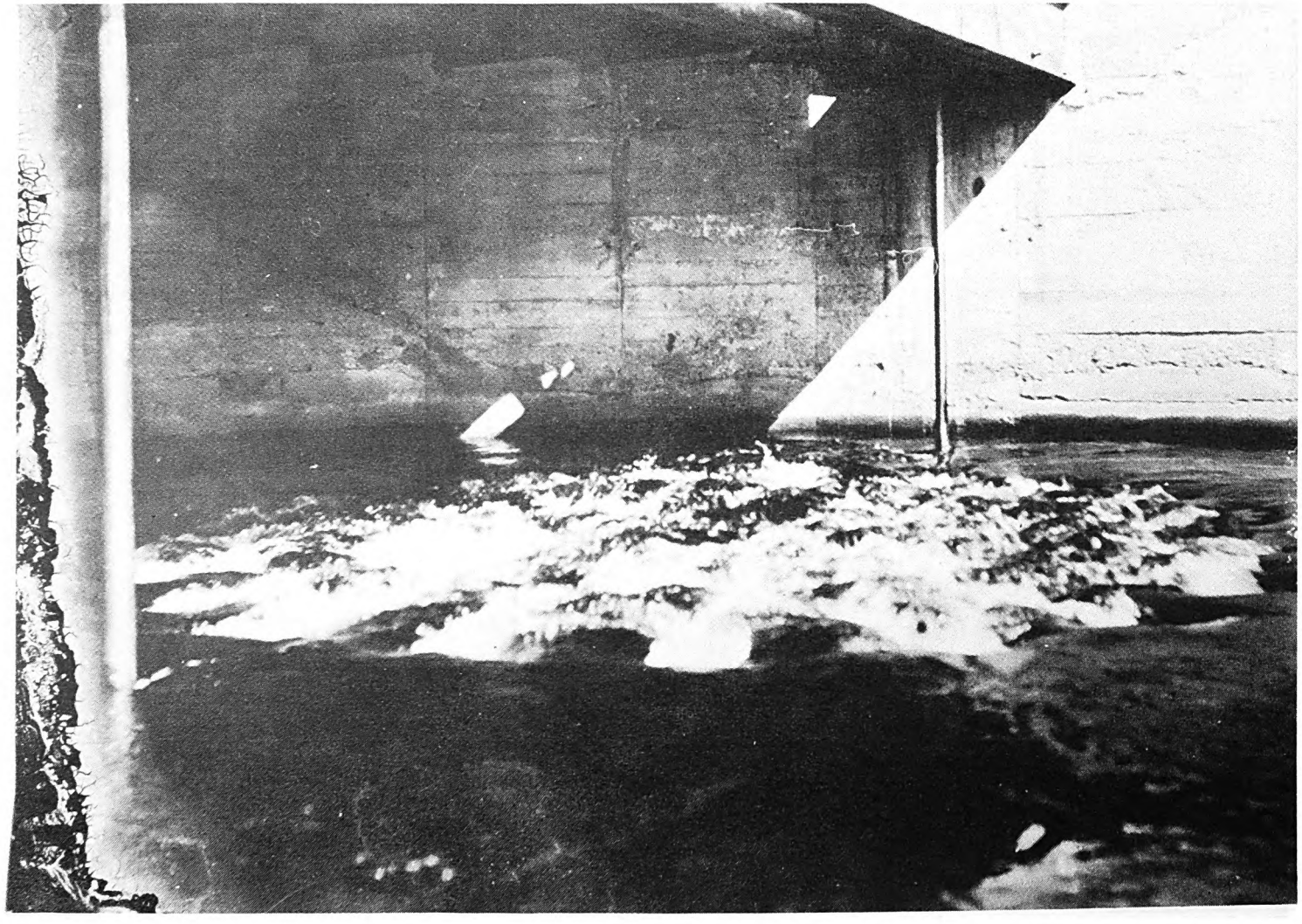

Figure 26. - Compressor intake heads in operation, Cobalt Hydraulic Power Co.—water and air emulsion entering the multiple 14-inch pipes. (Courtesy of Chas. H. Taylor (deceased), Toronto, Canada.)

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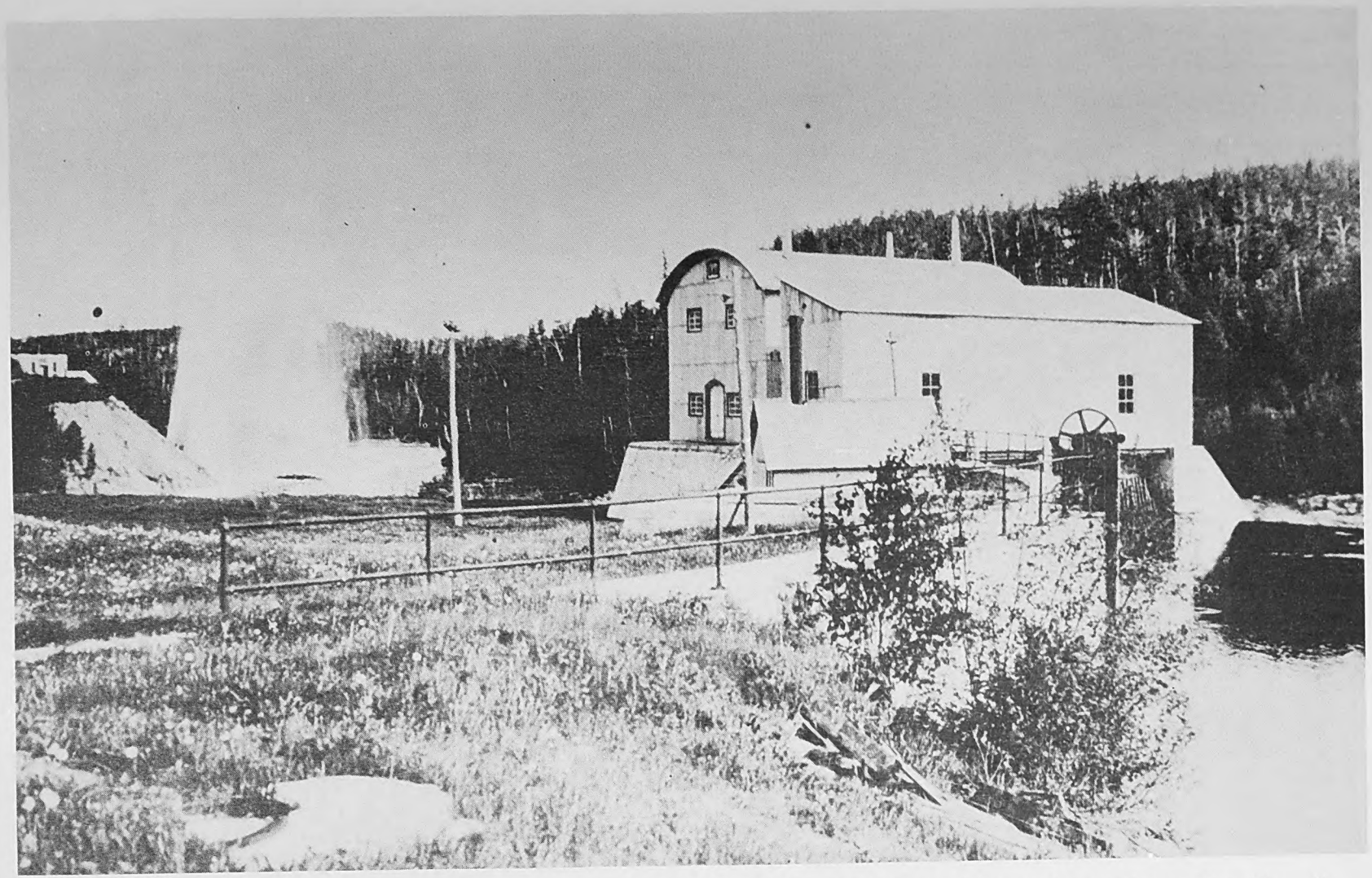

Figure 27. - Cobalt Hydraulic Power Co. compressor plant. General view of intake building and spray from safety blowoff pipe, 1945. (Courtesy of Hydroelectric Power Commission, Ontario, Canada.)

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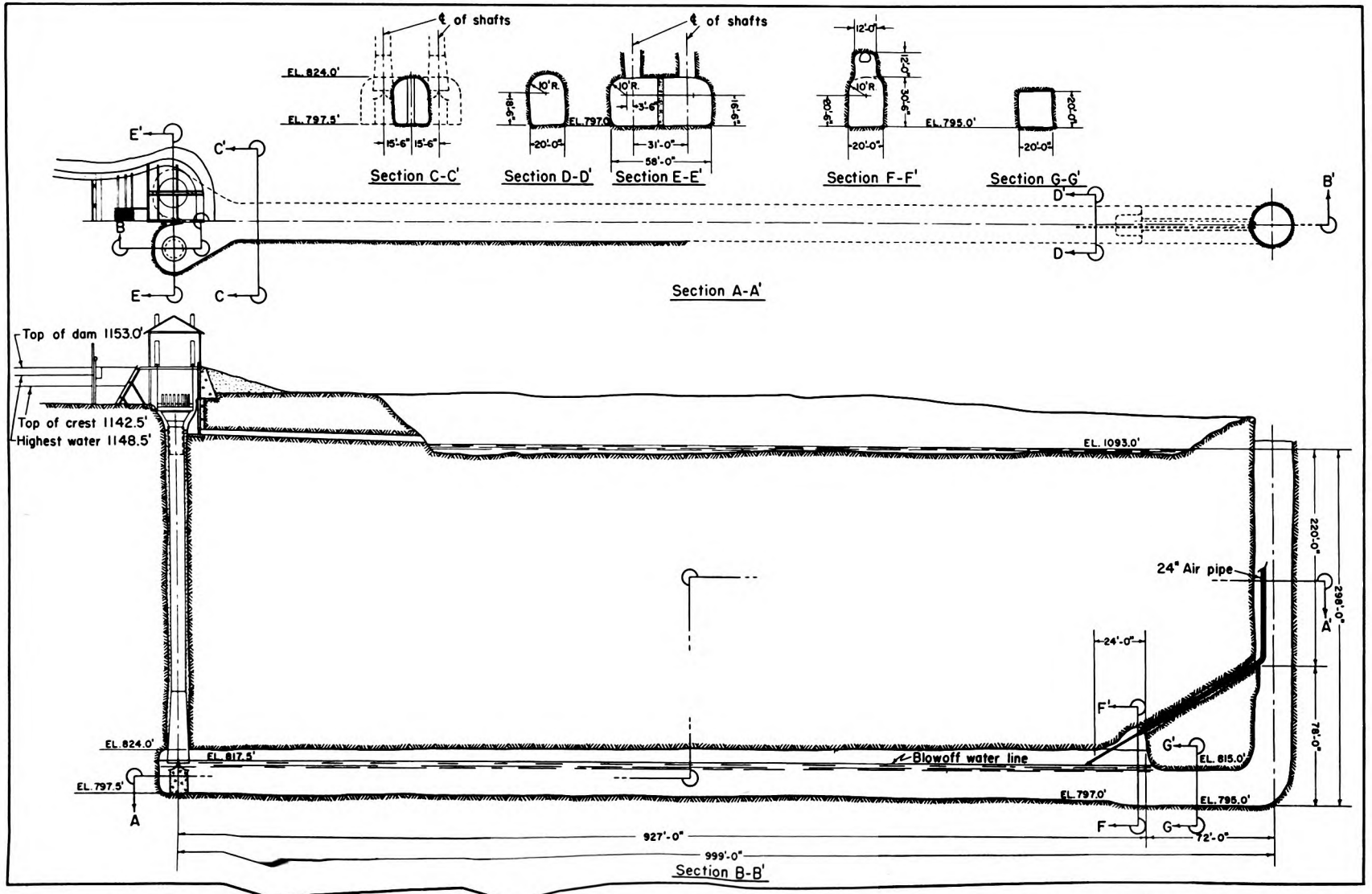

Figure 28. - Cobalt Hydraulic Power Co. compressor-design details, taken from construction drawings by Chas. H. Taylor, 1909. (Courtesy of Hydroelectric Power Commission, Ontario, Canada.)

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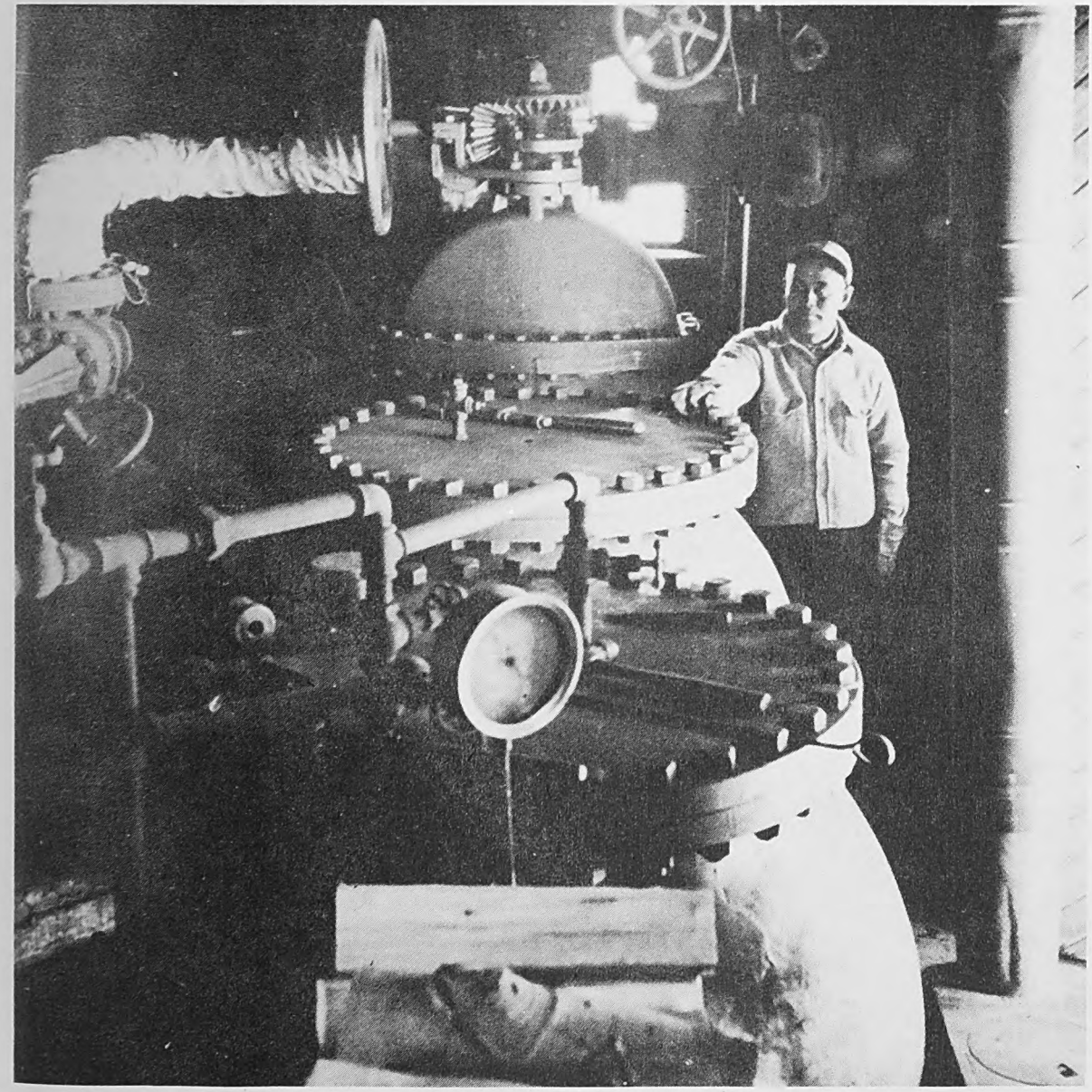

Figure 29. - Cobalt Hydraulic Power Co. compressor-valve-house equipment in operation, winter of 1949.

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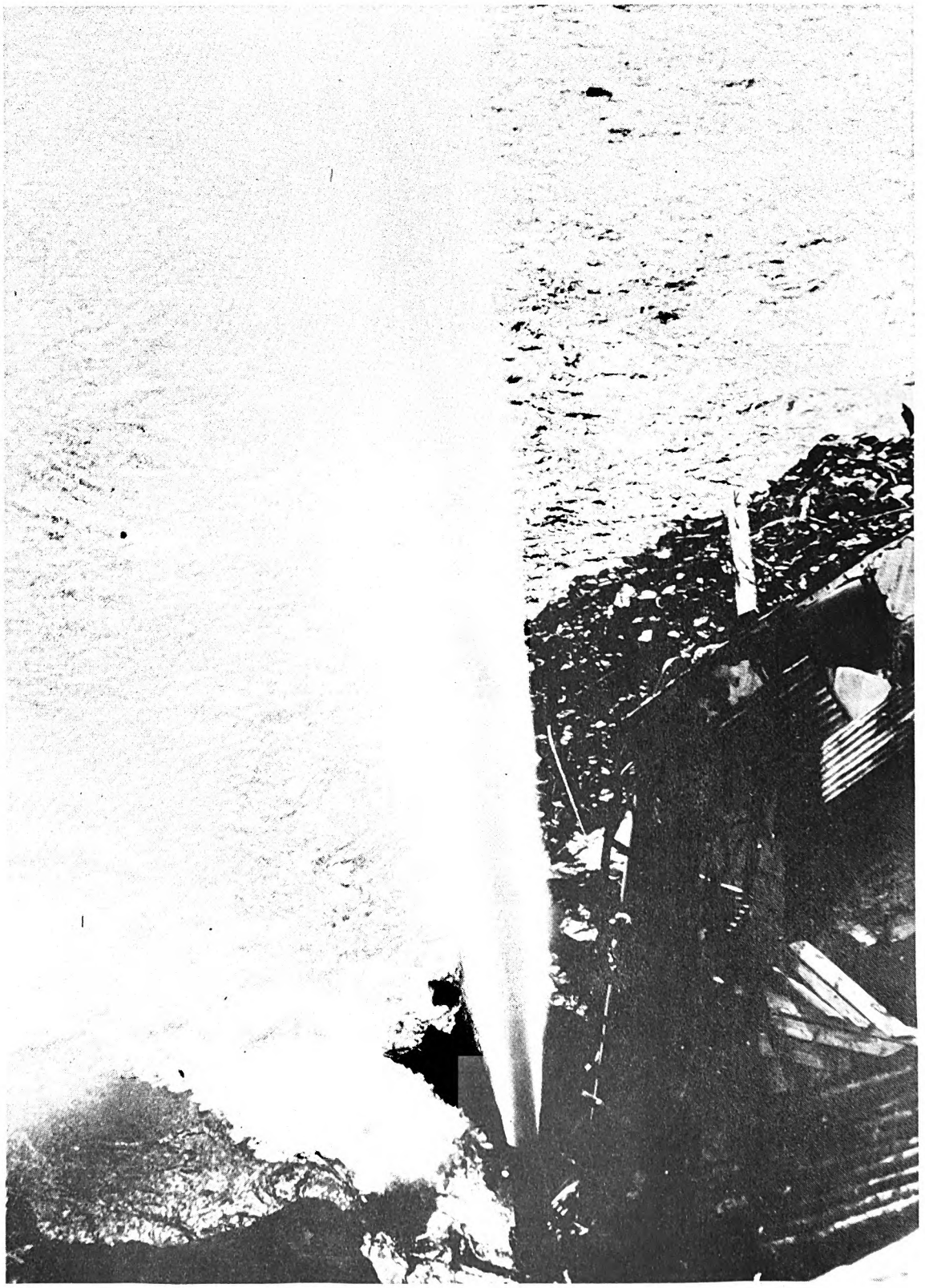

Figure 30. - Cobalt Hydraulic Power Co. compressor safety blowoff pipe in operation, 1945. This pipe has since been destroyed by ice action. (Courtesy of Hydroelectric Power Commission, Ontario, Canada.)

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The blowback destroyed one intake head and so damaged the concrete building over the intakes that it was not repaired but was replaced with a frame and sheet-steel building, which can be seen in figure 27.

Figure 28 (photocopy drawing of details taken from original drawings by Taylor in 1909) shows most of the features of the installation. The 2 downfall shafts with the steel sleeve at the top were 8 feet 6 inches in diameter and were concreted their entire length to the point where a 40-foot-long steel diverging section was attached. This 40-foot section increased from the shaft diameter to 12 feet 6 inches in diameter and extended 8 feet into the air chamber, forming a water seal when in normal operation. The air chamber is 20 feet wide and an average of 26 feet high for a distance of 927 feet. At that point the ceiling is reduced to 20 feet in height to form a seal for the stored air. The discharge tunnel, 20 by 20 feet in section and 60 feet long, carries the water to the 22-foot-diameter vertical discharge shaft. The air-storage chamber has about 200,000-cubic-foot volume.

The 24-inch-diameter air main rises up the discharge shaft and enters a regulator building, which houses a 24-inch meter, a regulator valve, and gate valves, shown in figure 29.

A 12-inch-diameter safety blowoff pipe was installed with its footpiece at the point selected for maximum air-storage capacity. This pipe and the 24-inch air main were anchored at 30-foot intervals to the side of the vertical discharge shaft. The safety blowoff extended about 10 feet above normal water level; the 24-inch air main angled up the steep bank to the regulator building (fig. 30).

From the meter building a 20-inch-diameter air main winds across hills and valleys, anchored and supported at intervals with concrete piers. Each section between piers is provided with a sliding expansion joint. Before World War I, when the system was in maximum use, the extent of all air lines, including the 12-inch, 10-inch, 8-inch, and 6-inch tributary lines running to the various mines, was as much as 100 miles. The larger sizes of pipe were purchased from Kattowitz, Germany, at a price reported to be $0.03 per pound delivered to Cobalt. One 20-inch-diameter section, 40 feet in length, weighed 3,000 pounds and cost $90 delivered.

During construction of the Cobalt hydraulic compressor, other interests were building hydroelectric plants; consequently, competition developed among the various companies to determine which would first get contracts with the mines to furnish air. The explosion at Cobalt and a serious drought during the winter of 1910 caused many of the mines to close because the hydroelectric plants were without enough water. The operators of the mechanical compressor plants pointed out that the hydraulic compressor lowered the oxygen content, and miners complained that their lamps did not burn as brightly in the air supplied by the hydraulic plant. Tests established the fact that the oxygen content ran about 17.7 percent rather than the normal 21 percent, but the hydraulic compressor operators pointed out the objections to mechanical compressors, which put excess free moisture into the lines and drills as well as the oil vapor associated with mechanical-air-compressor supply of air. Following an electric-rate war in 1911 between the hydroelectric plants that supplied the mechanical compressor plants, Northern Ontario Light & Power Co. was formed and took over operation of the hydroelectric plants and the hydraulic compressor plant.

This company continued to operate the various plants until 1944, when it, in turn, was purchased by The Hydroelectric Power Commission of Ontario. Inspection in 1945 disclosed that the hydraulic compressor needed substantial repairs caused

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by lack of maintenance. The two intake heads were damaged by logs and floating debris, and many of the 14-inch-diameter pipes were broken off or plugged. Air leakage was visible from the air chamber where it bubbled up through quiet pools in the river bottom or could be heard issuing from rock crevices. In addition, the pipelines leaked at gasketed joints, and the expansion joints were in poor condition. The airmeters had not been maintained, so that the quantity of air being delivered to operating mines was not accurately known. Nevertheless, during February 1950, available records showed that 10,978,800 cubic feet of compressed air at 100 p.s.i.g. had been sold to 14 operating mines at the rate of $0.25 for each 1,000 cubic feet of compressed air metered. Recent information indicates that a study is being made to determine whether to recondition the hydraulic compressor or to dismantle it after constructing a hydroelectric plant to utilize the available head.

UNITED STATES AND CANADIAN INVENTORS

From 1895 to 1924, considerable experimental work was done on the general subject of air compression and air-lift pumping. Names of several inventors interested in the subject at that time include: F. C. Starke, Milwaukee; W. O. Webber, Boston; W. J. Linton, Woodstock, Ontario; J. A. Inslee, St. Louis; A. G. Waterhouse, Springfield Twn., Pa.; R. I. Blakney, Seattle; F. P. Wilbur, Milwaukee; and A. O. Girard, Milwaukee. Prof. Joseph Hart, University of Pennsylvania, was interested in the hydraulic air compressor (22a) and recommended a form of bucket pump, which he thought more adaptable in certain cases. Prof. Elmo Harris, University of Missouri, studied the air compressor and the air lift pump (22b) and designed a successful "return-air displacement system" which was built into the Harlem River crossing of the Croton Aqueduct in New York City in 1905 (22c). Purchas (22d) reported (1917) tests of operating airlifts in oilwells at Oilfield, Calif., where an efficiency of 72.4 percent was obtained for the eduction pipe alone. Rix devoted considerable time, along with Dr. Julius Pohle (22h), to the design and testing of airlifts at San Francisco. Davis and Weidner (22i) conducted more than 600 tests on small model airlifts during 1908 to 1914. Ward and Kessler (22j) continued the work of Davis and Weidner from 1919 to 1924. Westinghouse Air Brake Co. (22k) conducted some 1,800 experiments on airlifting before 1908. Chodzko (22-l) wrote two analytical articles on the subject of hydraulic air compressors and proposed some simplified formulas for the general design. He stressed the low cost of operation and maintenance of the hydraulic air compressor and pointed out that it should be particularly adaptable for use in small mines or tunnels located in remote areas. In 1924 Sloan (22g) was associated with a development group in Philadelphia, which studied a unit called the "Hydrautomat" (a form of hydraulic air compressor and airlift combination), which had been developed in England.

FOREIGN INSTALLATIONS AND INVENTORS

Several men of other countries, all of whom obtained United States patents on their inventions, were active in the study and development of hydraulic air compressors for mining, irrigation, and dewatering uses from 1905 through 1927. Installations were made in England, Sweden, Germany, India, Pakistan, and Spain. Among this group were: Prof. M. F. Gutermuth, Darmstadt, Germany; Peter Bernstein, Mülheim-on-the-Rhine, Germany; O. H. Mueller, Camberwell, England; Carl Heirich, Cologne, Germany; and J. O. Boving, London, England.

Germany

Translation of several technical articles, which appeared in German publications, has permitted the writer to obtain what is considered to be a reasonably accurate picture of the development in Germany (23a). Bernstein, "overengineer" with the

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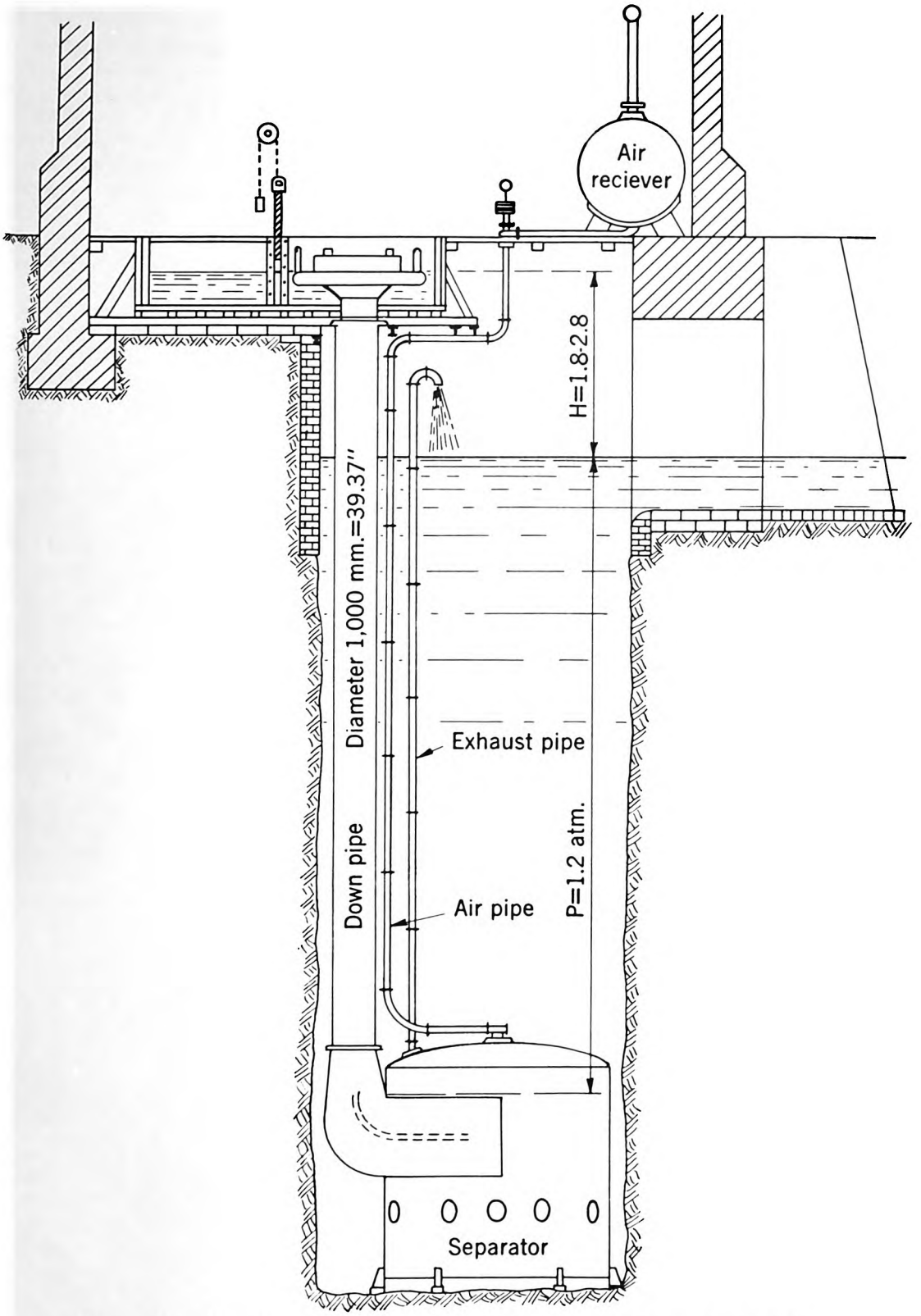

Figure 31. - Details of Dillingen test installation, Dillingen Iron Works, Germany. (Reproduced from Hydraulische Luftkompression-sanglagen by P. Bernstein, 1906, Glückauf.)

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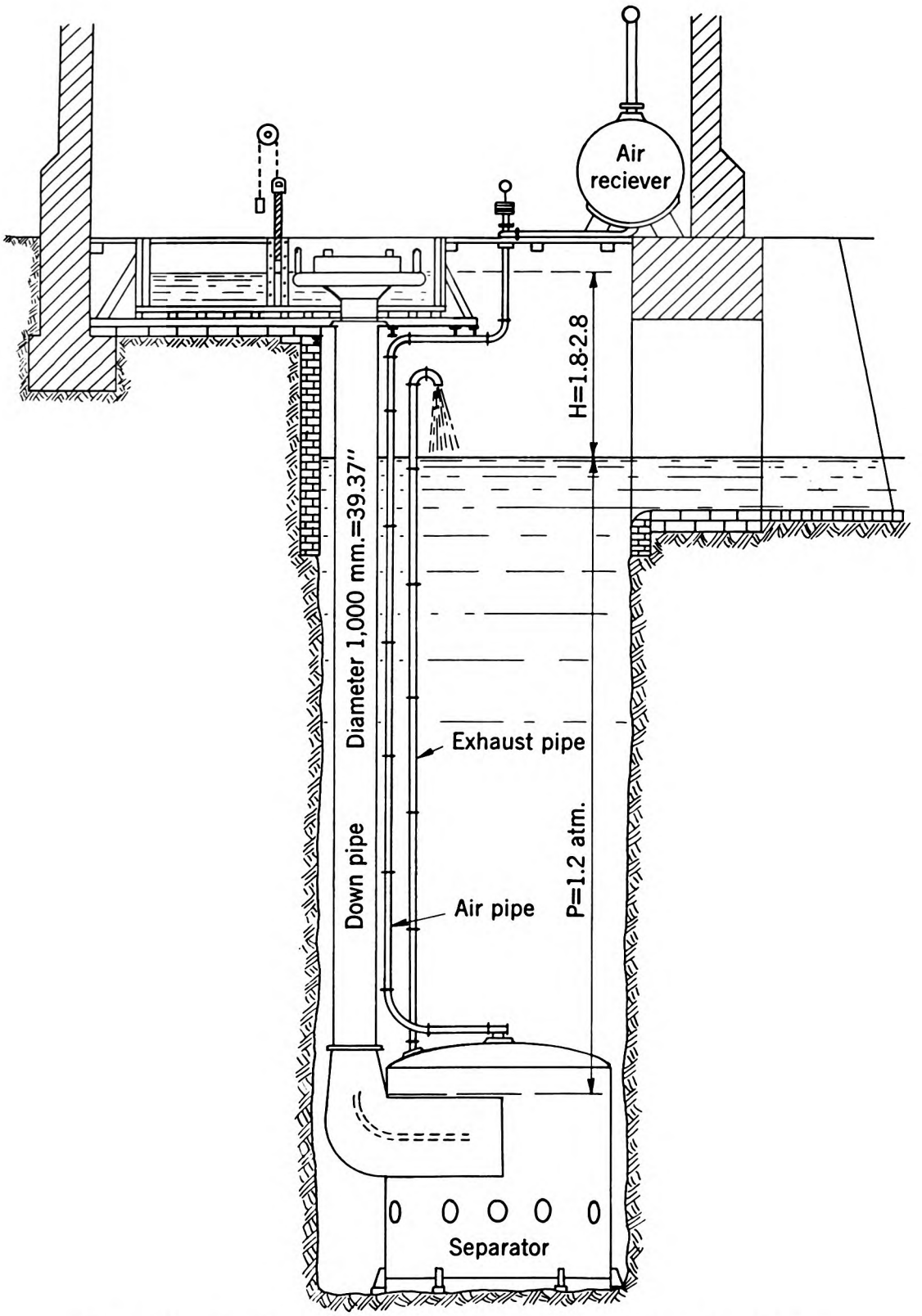

Figure 31. - Details of Dillingen test installation, Dillingen Iron Works, Germany. (Reproduced from Hydraulische Luftkompressionsanglagen by P. Bernstein, 1906, Glückauf.)

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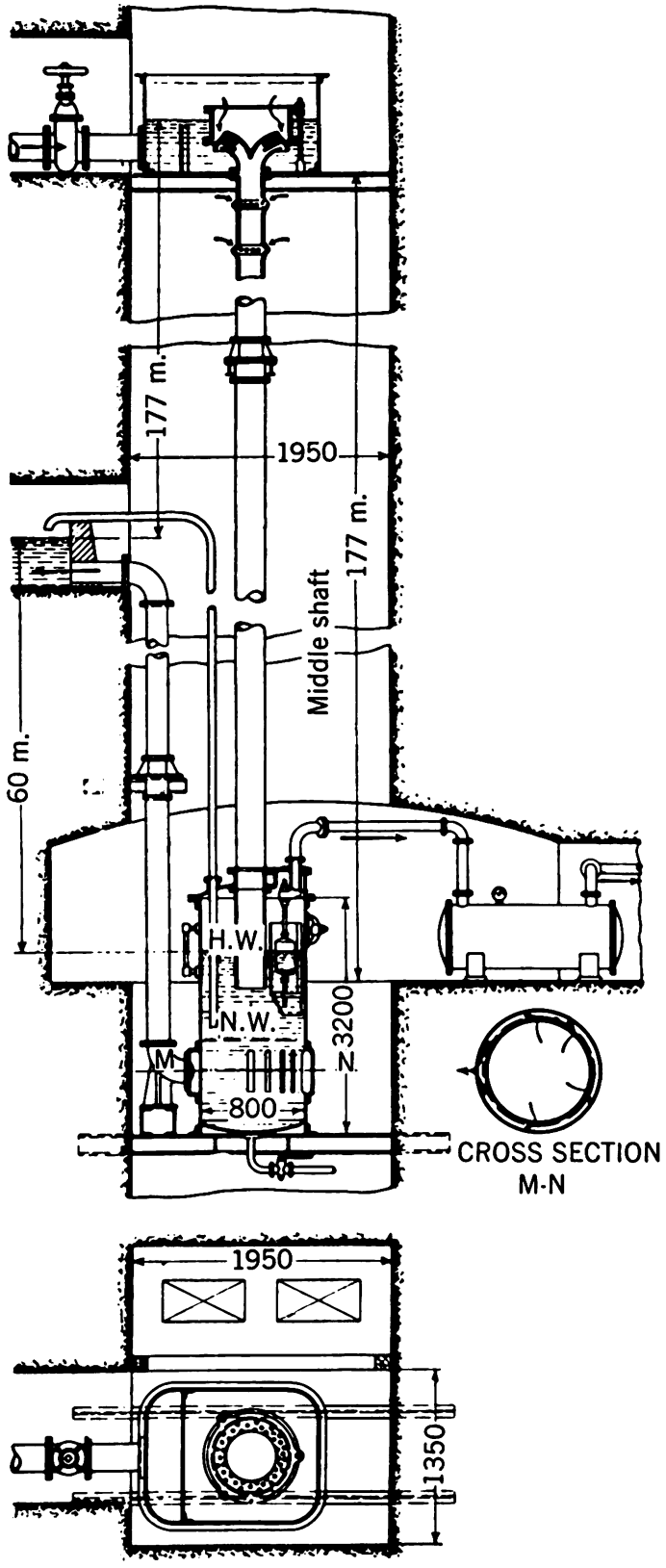

Figure 32. - Arrangement of Holzappel compressor, Holzappel mine, Laurenberg, Germany. (From Glückauf.)

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Wasser-Druckluft-Syndikat, Mülheim am Rhein, Germany, reports that Prof. Gutermuth, Darmstadt, became interested in the reports of the Magog and Ainsworth compressor installations in 1896 and 1897. Gutermuth undoubtedly had access to the report of Pearsall (10e) about the Magog compressor, which was made to the Manchester, England, meeting of the Association of Engineers in 1897. Gutermuth's interest led to the formation of a syndicate, called Wasser-Druckluft-Syndikat, to construct the first test installation in 1898 on the property of the Dillingen Ironworks, Dillingen on the Saar. This company had an unused water wheel, which included a 62-foot shaft in which the compressor was built. Bernstein shows a sectional drawing of this first German test unit (23a). Study of this detailed drawing shows that the suction-head was similar to the Magog design and that the air separator closely followed the Ainsworth compressor design, which had been reported in detail by Norman (11c) and others (11f) in 1898. According to Bernstein, Gutermuth first made public his study of the commercial possibilities of this type of compressor at the 25th annual jubilee of the Frankfort section of the United German Engineers in 1900. He discussed the Magog and Ainsworth units and the test unit at Dillingen.

Dillingen Test Installation

Figure 31 (taken from ref. 23a, p. 940) shows the Dillingen unit, and table 4 is the test data obtained by Gutermuth. The size of this test unit was limited by the old shaft, but the test was indicative of further installations for higher air pressures and use of greater and smaller water quantities.

TABLE 4. - Test data, Dillingen unit

Head = 1.8 meters
Air pressure = 1.2 atmospheres effective
Li = 7.88 m.-kg./liter air
La = 8.86 m.-kg./liter air 1/ 2/

Water, liters per second	Air velocity, meters per second 3/	Water, hp.	Air quantity, liters per second	Compressor power		Calculated efficiency	
				Isothermal	Adiabatic	Isothermal hp.	Adiabatic hp.
416	0.63	9.8	55	5.7	6.5	0.58	0.66
487	.93	11.4	81	8.6	9.6	.75	.84
522	1.06	12.4	92	9.7	10.9	.78	.88
637	1.35	15.0	117	12.2	13.8	.81	.92
657	1.37	15.4	119	12.5	14.1	.81	.92
718	1.52	17.0	132	13.7	15.6	.80	.92
768	1.57	18.2	137	14.4	16.2	.79	.89
823	1.63	19.5	142	15.0	16.8	.77	.86
848	1.65	20.3	143	15.1	16.9	.74	.83
868	1.66	20.8	144	15.3	17.0	.74	.82

1/ Li = Isothermal compression work.
La = Adiabatic compression work.
2/ m.-kg. = meter - kilogram.
3/ 1 meter air velocity per second = 14.5 liters of air drawn in per second. Velocity of air intake in meters per second is for air taken in at each of the six intake pipes leading to the annular ring pipe (modelled after the Magog intake head) so that the air quantity is equal to Air Velocity in meters/second x 14.5 x 6. For example: 0.63 x 14.5 x 6 = 55 liters/second.

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Glanzenberg Shaft Test Installation

Several mines in the Harz Mountain area had adits opening along the slope, which were used to discharge mine water. Suitable conditions were found in the Glanzenberg shaft near Siegen, and a compressor was built into an unused part of the mine. Water having a maximum flow of 300 g.p.m. (19 liters per second) was developed at a point 250 feet below ground. The fall tube was made 3.93 inches in diameter (100 mm.), with means for movement of the suctionhead from 1 level to another so as to secure test data at 2 different values of total head, that is, 472 and 343 feet. Tables 5, 6, and 7 are results of several tests made with varying head and with approximate back pressures of 120 and 105 p.s.i.g. held on the air-separator tank with a valve. Bernstein reports (23a, p. 937) that, as a result of the good efficiency obtained at Glanzenberg, commercial installations were made.

TABLE 5. - Test data, Glanzenberg unit

Head = 40 meters — Li = 21.97 m.-kg./liter air
Air pressure = 8 atmospheres effective — La = 30.66 m.-kg./liter air 1/ 2/

Water, liters per second	Air velocity, meters per second 3/	Water, hp.	Air quantity, liters per second	Compressor power		Calculated efficiency	
				Isothermal	Adiabatic	Isothermal hp.	Adiabatic hp.
9.0	0.75	4.8	11.0	3.2	4.5	0.66	0.94
11.3	1.01	5.85	14.9	4.3	6.1	.72	1.04
14.2	1.32	7.25	19.1	5.6	7.8	.74	1.07
16.2	1.45	8.2	20.9	6.2	8.55	.71	1.04
16.7	1.415	8.4	20.5	6.05	8.38	.68	.99

1/ Li = Isothermal compression work.
La = Adiabatic compression work.
2/ m.-kg. = meter - kilogram.
3/ 1 meter air velocity per second = 14.5 liters of air drawn in per second.

TABLE 6. - Test data, Glanzenberg unit

Head = 50 meters — Li = 20.79 m.-kg./liter air
Air pressure = 7.0 atmospheres effective — La = 28.47 m.-kg./liter air 1/ 2/

Water, liters per second	Air velocity, meters per second 3/	Water, hp.	Air quantity, liters per second	Compressor power		Calculated efficiency	
				Isothermal	Adiabatic	Isothermal hp.	Adiabatic hp.
8.7	0.82	5.8	11.8	3.3	4.5	0.57	0.78
10.0	1.03	6.6	14.75	4.1	5.6	.62	.85
11.4	1.25	7.6	18.0	5.1	6.8	.66	.90
12.5	1.40	8.3	20.0	5.7	7.6	.68	.92
13.8	1.50	9.2	23.0	6.3	8.7	.69	.95
14.7	1.70	9.8	24.5	6.8	9.3	.70	.95
15.1	1.72	10.0	25.0	6.9	9.5	.69	.95
16.5	1.88	11.0	27.5	7.6	10.4	.69	.94
18.0	2.03	12.0	29.0	8.2	11.0	.68	.92

1/ Li = Isothermal compression work.
La = Adiabatic compression work.
2/ m.-kg. = meter - kilogram.
3/ 1 meter air velocity per second = 14.5 liters of air drawn in per second.

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TABLE 7. - Test data, Glanzenberg unit

Head = 17 meters
Air pressure = 7 atmospheres effective
Li = 20.79 m.-kg./liter air
La = 28.45 m.-kg./liter air 1/ 2/

Water, liters per second	Air velocity, meter per second 3/	Water, hp.	Air quantity, liters per second	Compressor power		Calculated efficiency	
				Isothermal	Adiabatic	Isothermal hp.	Adiabatic hp.
7.0	0.252	1.52	3.7	1.00	1.40	0.657	0.920
8.2	.302	1.83	4.4	1.20	1.67	.657	.912
9.3	.330	2.10	5.2	1.46	2.01	.680	.957
10.6	.416	2.40	6.05	1.66	2.30	.692	.959
11.8	.440	2.66	6.75	1.87	2.56	.692	.961
12.6	.490	2.85	7.1	1.95	2.70	.692	.948
14.2	.565	3.20	8.2	2.25	3.12	.702	.975
16.5	.595	3.73	8.65	2.38	3.28	.643	.880
17.6	.580	3.98	8.5	2.32	3.23	.582	.812
18.5	.580	4.20	8.5	2.33	3.23	.582	.770
19.6	.540	4.45	8.0	2.20	3.04	.493	.683

1/ Li = Isothermal compression work.
La = Adiabatic compression work.
2/ m.-kg. = meter - kilogram.
3/ 1 meter air velocity per second = 14.5 liters of air drawn in per second.

Holzappel Mine at Laurenberg

The first commercial installation was made in 1905 in the Holzappel mine of the Rheinisch-Nassauische Bergwerks- und Hutten A. G. An unused shaft was available for installation of the fall tube (fig. 32). Water supply was collected in several ditches along the side of the mountain, and from the lowest point a 12-inch-diameter, cast-iron pipe conducted the flow about 1,500 feet to the shaft location. About 160 feet below the surface level a tank was built to house the suctionhead, and the water pipe was connected to this tank. Approximately 380 feet below the tank location there was an outlet from this shaft leading to the slope of the mountain, which provided an ideal discharge for the compressor water. The suctionhead was similar to the Magog and Ainsworth units, but only about 30 inches in diameter. The 5-inch-diameter fall tube was approximately 575 feet long and entered a vertical tank about 3 feet in diameter by 10 feet high, which served as the air separator. Slots on the sides of the tank permitted the water to escape. It is also obvious that water would carry some of the air out these same slots. The compressor design was based on the maximum waterflow of 472 g.p.m. (30 liters per second). During tests conducted by Bernstein and a representative of the mining company, an isothermal efficiency of 60 percent was obtained at full flow. Table 8 shows test results obtained. That the air separator was inefficient is indicated by the increased isothermal efficiency of 66 percent obtained when the flow was reduced.

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TABLE 8. - Test data, Holzappel unit

Head = 117 meters
Air pressure = 6.2 atmospheres effective
Li = 19.70 m.-kg./liter air
La = 26.67 m.-kg./liter air 1/ 2/

Water, liters per second	Air velocity meters per second	Water, hp.	Air quantity, liters per second	Compressor power		Calculated efficiency	
				Isothermal	Adiabatic	Isothermal hp.	Adiabatic hp.
18.0	-	28.4	72	18.9	25.6	0.66	0.90
30.5	-	47.6	108	28.5	38.5	.60	.81
32.2	-	50.2	112	29.5	40.0	.59	.80
35.7	-	55.6	114	29.9	40.4	.54	.73

1/ Li = Isothermal compression work.
La = Adiabatic compression work.
2/ m.-kg. = meter - kilogram.

Royal Mine Inspection Plant at Clausthal

Bernstein reports (23b) further development in designs used by his company in the Royal installation built in 1907 in the Altensegen shaft of the mine at Clausthal. This compressor replaced a Pelton waterwheel-driven compressor and made use of the existing waterline, which formerly supplied the waterwheel. Figure 33, taken from the above reference, shows the multiple annular air rings that were used, as well as the improvement in the air-separator construction over that used in the Holzappel mine at Laurenberg (fig. 32). The shaft into which the compressor was built had a 22° bend from the vertical at the point just below the suctionhead location, which, in the writer's opinion, accounts in part for the relatively low operating efficiency obtained during acceptance tests on the compressor.

The suctionhead was at Tiefer Georg level, a point about 980 feet below surface. A drainage basin at Ernest-August level, 1,305 feet below surface, was used for the compressor discharge, thus providing 325 feet of fallhead. The air separator, which was 43 inches in diameter and 177 inches high, was 170 feet below the discharge point. With this head on the separator, the compressed air was developed at about 74 p.s.i.g. Both the fall tube and the discharge tube were sectional lengths of 8-1/2-inch-diameter pipe connected with regular pipe bends, which also added to the frictional loss. Over 500 feet of pipe from the suctionhead to the separator and 250 feet from separator to discharge created a substantial pipe-friction loss chargeable to compressor efficiency. During the guarantee test, 3.2 cubic meters per minute (845 gallons per minute) water flow was used, and delivered air was 353 c.f.m. free air compressed to 72 p.s.i.g. Adiabatic efficiency was calculated to be 77 percent.

Royal Mine-Inspection Plant at Grund(in the 4th light-shaft)

Bernstein reported on the details of this installation, which was made in 1909, at a meeting in Cologne in 1910 (23c, 23d). Figure 34 (23c) shows the general arrangement of support above ground, the fall tube, and the location of the double air separator. Figure 35 is a reproduction of a photo of the steel structure that supported the air suctionhead. The suctionhead was arranged with two sets of air-inlet rings in series, but both supplied from the one water pipe so as to have some control over the air intake as the available water supply varied. Water was supplied to the compressor from a 16-inch diameter pipe, which had supplied a small hydroelectric installation used to develop power for crushing ore. The supply pipe, 196 feet long, was under

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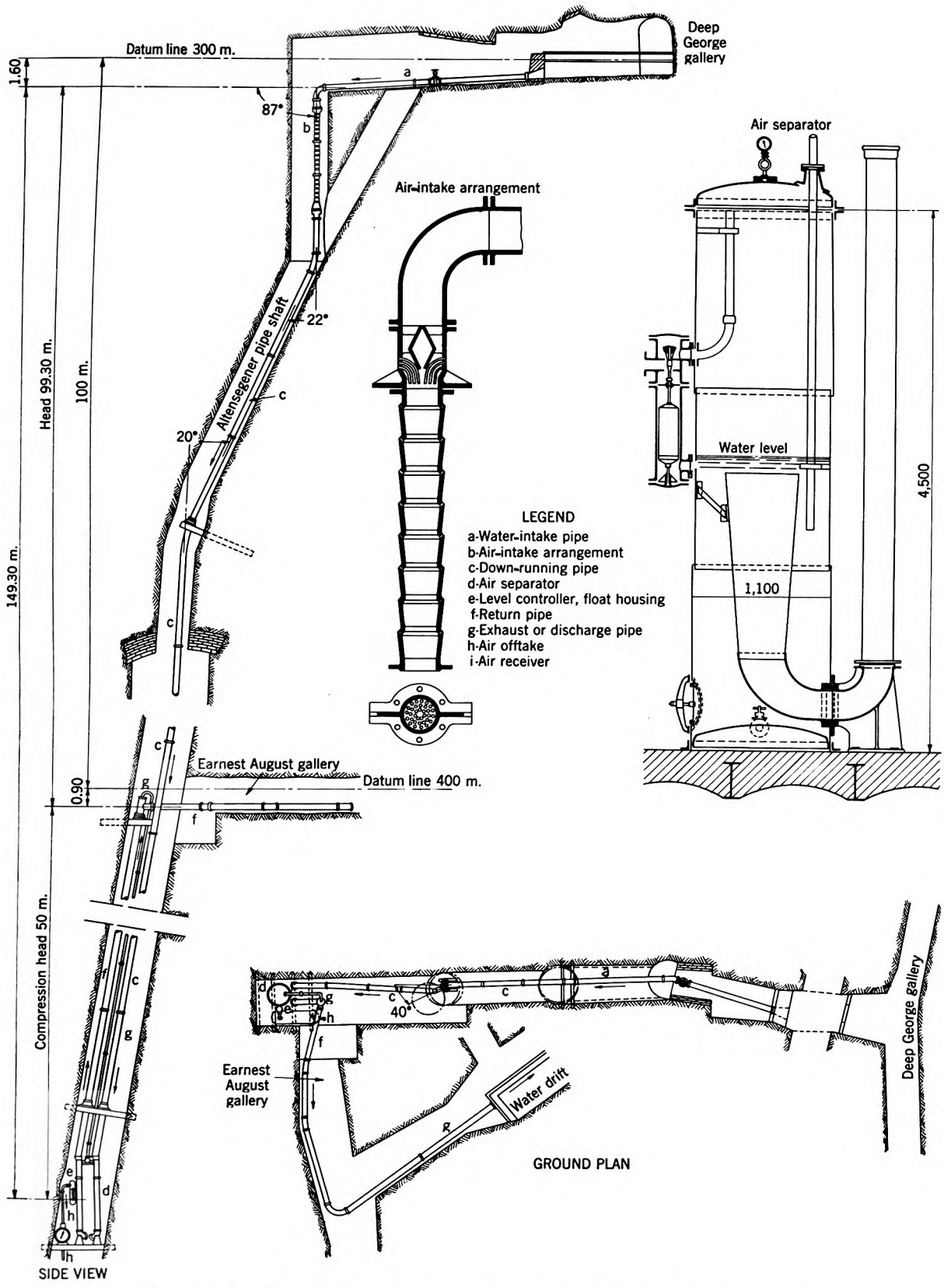

Figure 33. - Clausthal compressor, Altensegen shaft, Royal mine plant, Clausthal, Germany. (From Glückauf.)

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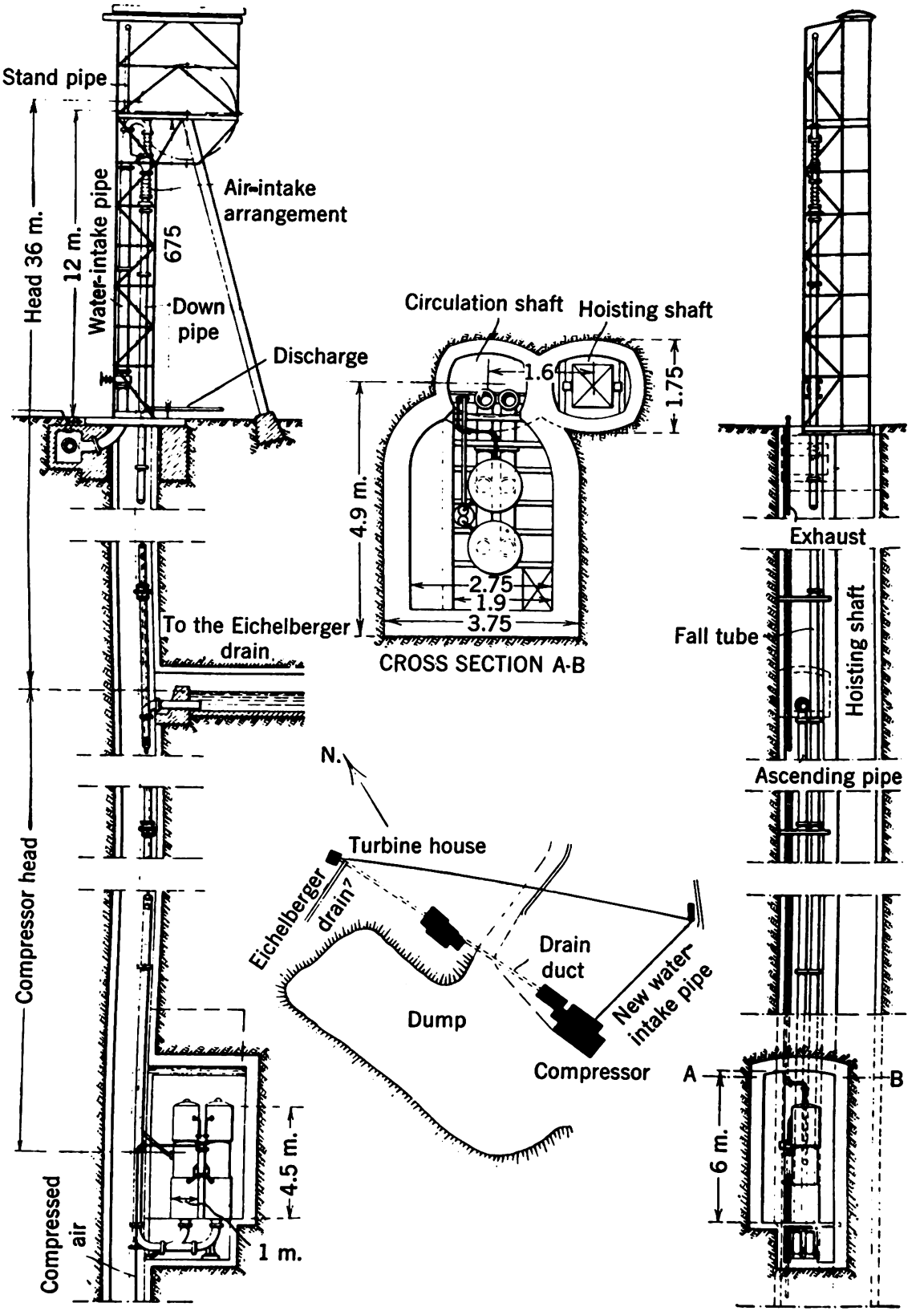

Figure 34. - Drawing of Grund compressor, 4th light-shaft, Royal mine plant, Grund, Germany. (From Glückauf.)

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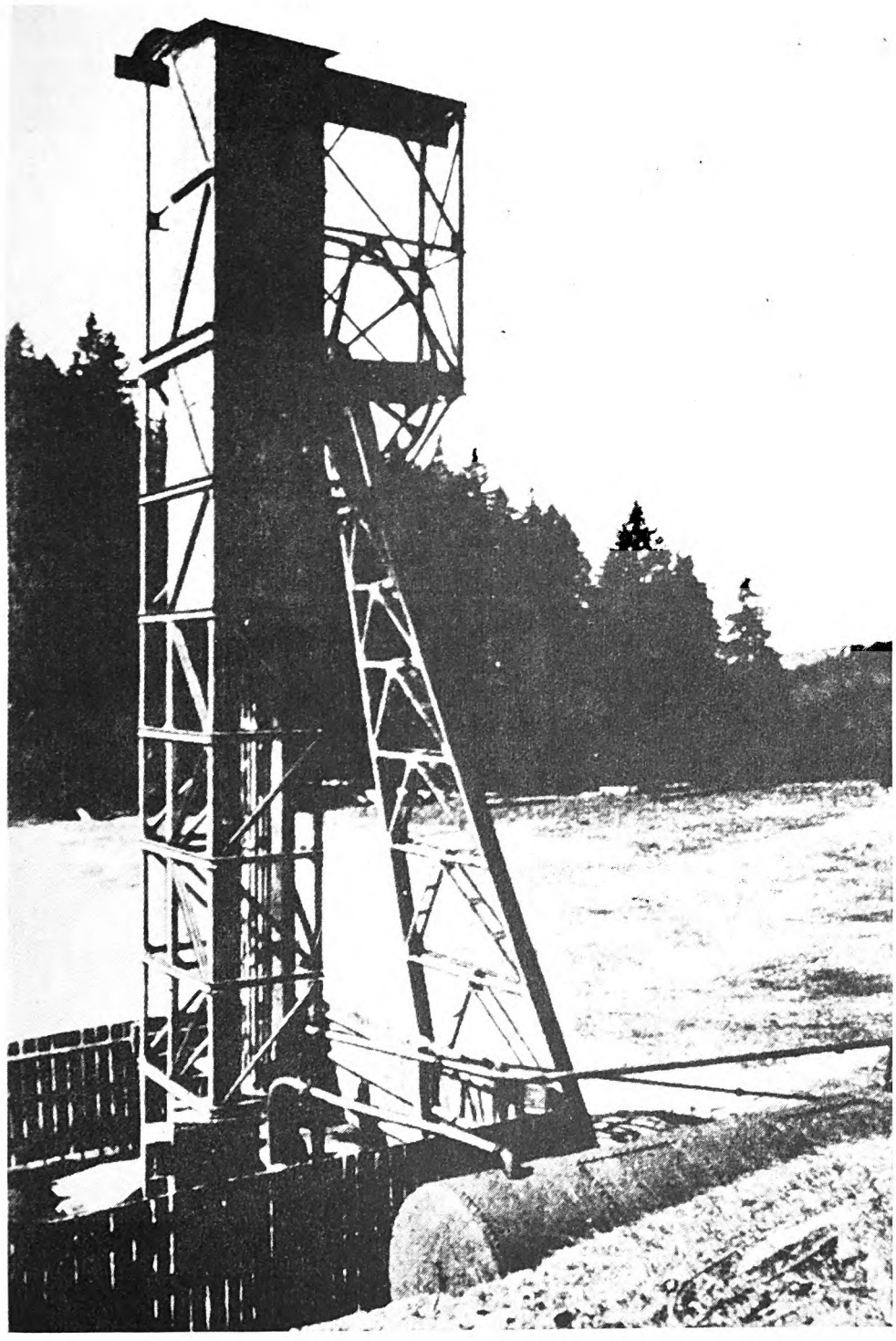

Figure 35. - Reproduction of a photograph of the Grund intake construction, Grund, Germany. (From Glückauf.)

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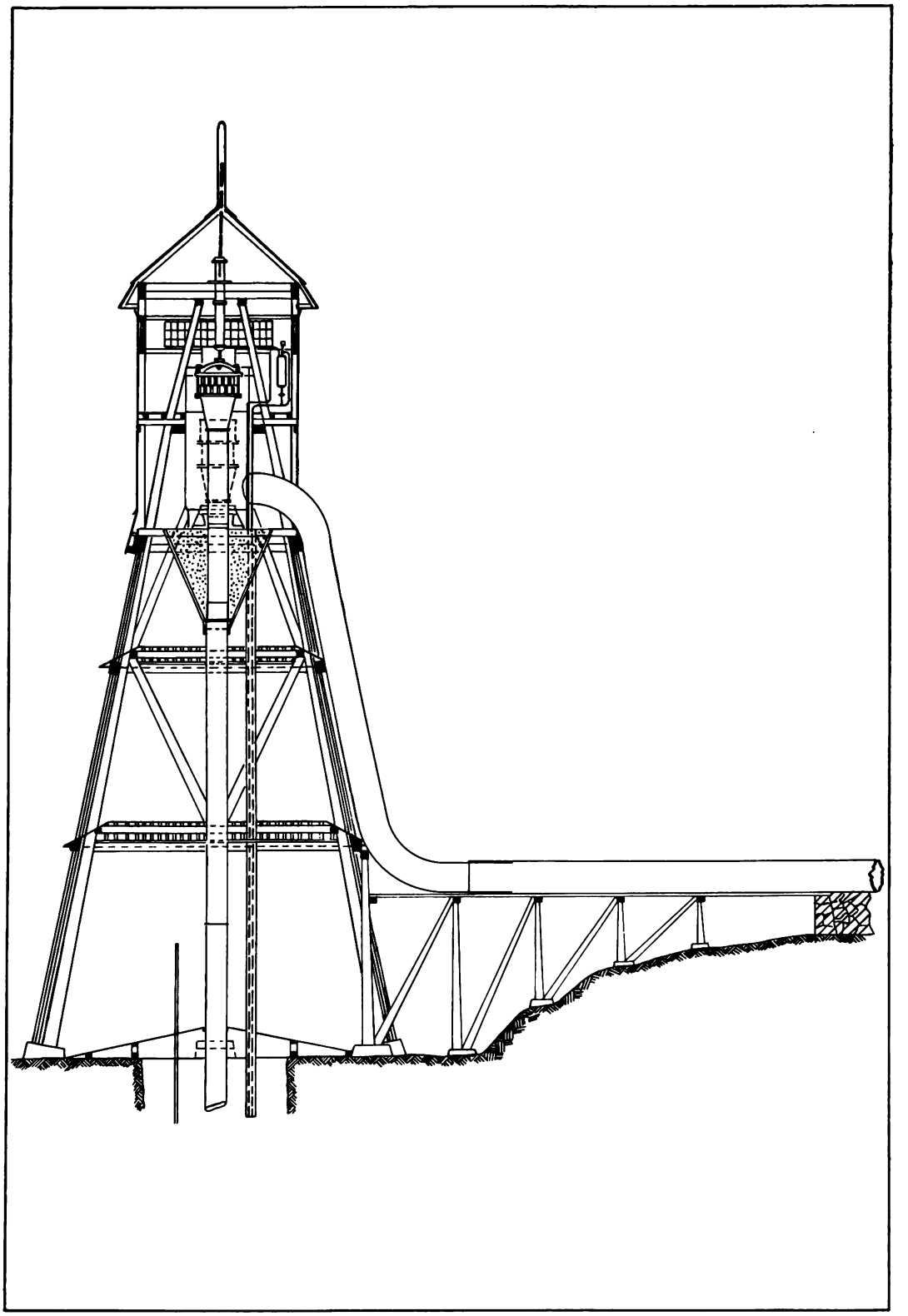

Figure 36. - Drawing of Persburg compressor showing tower, conduit, intake head, and fall tube, Persburg Mine Co., Sweden. (Reproduced from publication of Swedish installation by K. F. Brunnberg, 1911-18.)

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enough pressure to deliver water to the elevated suctionhead on the tower 39 feet above ground level at the shaft. By elevating the suctionhead this pressure head was used efficiently. The outlet for discharge water from the compressor was at a level that provided a 118-foot head. The double tank air separator was installed about 197 feet below the discharge level, which head provided 88 p.s.i.g. pressure on the compressed air. The fall tube and the discharge pipe were about 12 inches in diameter, of spiral-welded steel plate. The small size, double-tank, air separator (each tank 39 inches in diameter and 13 feet high) was designed for space limitations and to permit installing them through existing shaft openings.

In March 1910, after suitable measuring means had been determined, Bernstein and the mine supervisor, Borghardt, made a test of air production by filling a 39.5 m.3 air tank and measuring the water flow required to pressure this tank. They calculated they obtained 11.56 m.3 of free air per minute compressed to 88 p.s.i.g. with consumption of 9.425 m.3 of water per minute falling through a head of 118 feet. Theoretical adiabatic compression was calculated at 66.7 hp., and water horsepower was calculated at 75.5 hp. to give an efficiency of 88.5 percent (adiabatic).

Bernstein comments on an interesting comparison made with two electric-driven air compressors that were in operation at this mine to supply the air requirements. The 2 compressors were rated to supply 13 m.3 per minute of free air, but the hydraulic air compressor actually filled the test air receiver in less time than the mechanical compressors. The 13-m.3-per-minute rating did not take into account the fact that the mechanical air compressors delivered air at an elevated temperature, which upon entering the air receiver dropped in temperature and volume. The 2 motor-driven compressors required 90 hp. of electrical energy, which in turn required about 140 hp. of water power at the water wheel inlet. As a result of this comparison of 140 to 75.5 hp., required for producing air by the hydraulic compressor method, there was no doubt that the change was an economic one.

Compressor at Zeche Victor Rauxel at Dortmund

A somewhat unusual installation was reported by Bernstein (23d) at this mine, where no existing hydraulic head was available in the mine shafts. Water, which had to be pumped out of a lower level to an existing discharge basin, was elevated 270 feet farther where it entered a double air inlet similar to that used at Grund. The 10-inch-diameter fall tube dropped 460 feet where it entered the bottom of the air separator. Discharge from the separator flowed up to the discharge basin 197 feet above and produced an air pressure of 88 p.s.i.g. The compressor delivered 350 c.f.m. free air compressed to 88 p.s.i.g. while consuming 1,056 g.p.m. of water.

Bernstein visited the Magog, Ainsworth, and Victoria compressor installations in 1905 and subsequently wrote a short summary of his findings (23a). Again in 1908 he visited the United States and Canadian installations.

Review of Experiences and Operation of the Harz Mountain Compressors (1921)

A studious review and appraisal of the operation of the various installations of the hydraulic air compressor in the mining area of the Harz Mountains was made by K. Rubach, Grund, in 1921 (23e). It is interesting to note that, from the date of the last known article by Bernstein in 1910, several additional compressors were built into mine workings, but little publicity was given to these later units. Rubach mentions the installations in the Altensegen shaft at Clausthal, the fourth light shaft (IV Lichtschacht) at Grund, and then mentions others "for example" (which indicates that his list is not complete) at Kaiser-Wilhelm shaft in Clausthal, Duke Ernst August shaft in Bockwiese, and Knesebeck shaft in Grund.

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Rubach reports several factors in connection with the problem of building the compressor in the Knesebeck shaft at Grund and mentions some of the early errors made at the other installations. The somewhat concentrated location of the various hydraulic compressor installations was a result of the water conditions found in the upper Harz Mountains. Water that collected on the slopes of the mountains and mine water pumped out of various adits was conducted by canals and ditches along the face of the mountains to supply a number of small hydroelectric installations. At Gittelde, a 16-mile-long adit, known as Ernst-August adit, discharged the assembled flow to the plain at the foot of the mountain.

The Knesebeck shaft was a considerable distance from the water-supply canal but not far from the fourth light shaft compressor installation also at Grund. In 1912, based on experience at the fourth light shaft compressor, it was decided to replace turbine-driven air compressors with a hydraulic compressor. A flow of about 2,640 g.p.m. was available,and the total fallhead was 136 feet from canal to discharge. The initial design called for construction of a 65-foot tower at a point about midway down the slope from the canal to the shaft to hold the suctionhead. From the bottom of the tower, the fall tube angled down the slope at about 23° and entered the shaft. It was found that the flat pitch of the fall tube caused unstable conditions and therefore unsuccessful operation, undoubtedly owing to separation of air from the water. The tower was then rebuilt directly over the shaft. The height was increased to 154 feet but still obtained adequate flow in the supply pipe. Originally the suctionhead was of the double, air-inlet type developed by Bernstein, and had two sections of air rings arranged one above the other. However, both were supplied from the same waterline. This complicated piping pattern was intended to provide the maximum amount of air into the water by separating it into many ring-shaped jets with air entering through hundreds of small openings around the rings. Part of the theory followed by Bernstein was that the water must move at high velocity to create a vacuum as it passed the air rings. However, whenever the water supply fluctuated, air or water was forced out of the air-ring openings; in severe winter weather this caused such an ice load to form on the tower that it was impossible to service the suctionhead. Modifications were tried, and the jet velocity flow was found to be unnecessary. The head necessary to obtain the jet velocity was saved. The fourth light-shaft suctionhead was modified, and about 12 feet of head was saved. The first suctionhead design at Knesebeck used about 28 feet of head to obtain the high velocity, which was saved by further raising of the suctionhead and a 20-percent loss originally charged to the suctionhead design was eliminated. Suctionhead designs were greatly simplified and were substantially cheaper. The final design will be discussed later in connection with the Swedish compressors.

Rubach mentioned a suctionhead design that was somewhat automatic; no details are known, however. Reference may have been to Taylor's design at Victoria or Cobalt. No mention is made of any explosive blowback at any of the German compressors; but this was experienced and considered in design of the Swedish compressors, which were quite similar to the arrangement finally made at Knesebeck. Rubach refers to experiments in 1912 to 1915 by Heirich on the design of suctionhead. Heirich found that a small fall of water breaking into spray and then in turbulence entering the fall pipe produced a most satisfactory entrainment of air, while at the same time not consuming a large hydraulic head as required by the former jet-velocity designs of Bernstein. It will bear repeating at this point that Frizell (8) called attention to the results he obtained in his experiments in 1880 at Minneapolis, Minn., and recommended "that throwing the water into commotion is a perfectly effective mode of impregnating it with air." Frizell also stated, "any arrangement of pipes for this purpose appears to the writer entirely superfluous, as well as very objectionable." So it seems evident that Heirich reestablished facts known and published several years before his experiments.

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Rubach writes that considerable study was made of air leakage from the small-size air separators used in the German installation. In some installations double separators were installed, with good results, but in none of the installations did they go to the large size used by Taylor because of cost of construction and leakage in rock chambers.

All of the German units in the Harz Mountains were built into the existing light shafts (ventilating shafts), which could accommodate the piping and the air separator at a suitable level to secure desired pressure. In this way installation costs were kept to a minimum. The air-carryover losses from the air separator were known, but the steel air receiver was preferred to a costly rock chamber, with its problem of caulking cracks to reduce leakage. By building bulkheads and caulking old drifts, some installations used these for storing compressed air. They would be filled during off periods. The literature does not disclose any use of the hydrostatic air-storage chamber design used in this country and also constructed by the Swedish technicians, as discussed later.

A recent communication informed the writer that during 1950 consideration was being given to installation of hydraulic compressors for special purposes in the Ruhr mining area, but no details are available at this time.

Sweden

The earliest reference to any study of the hydraulic air compressor for use in Swedish mines is a paper by K. G. Brunnberg (24a) in 1911. Brunnberg, general manager of Persberg Mine Co., reviewed the development and installations made by Taylor and the several German units then in operation. That Brunnberg's interest was aroused is evident from his second paper (24b), given in 1918, in which he recounts the developments made since 1911 by his company.

In 1911, Brunnberg and Engineer G. Anderson, of the New Atlas Co., Stockholm, inspected the compressor units at Clausthal, Grund, Laurenberg, and Dortmund, Germany. After making comparisons between the German special designs and the Taylor details given in the literature, they decided that conditions at Persberg required a solution somewhat different. Before beginning design of the compressor, 2 test units were built by Anderson - 1 at the Atlas plant in Stockholm and 1 at the Alabama shaft at Persberg. Both test units were designed to use water at 41 g.p.m. The Atlas test unit had a 39-foot fallhead and compressed air to 17-1/2 p.s.i.g. The Persberg test unit had a 97-foot fallhead and compressed air to about 100 p.s.i.g. Anderson tested several designs of suctionhead and used the German experience to good advantage.

Estimates of cost for the hydraulic compressor showed it to be higher than either a hydroelectric power plant or a turbine-driven air-compressor plant, but information available on low operating and maintenance costs of the hydraulic compressor led to its selection.

Persberg Mine Co. Compressor

Work was begun in 1911 with the construction of a canal 10,000 feet long from the Horrsjoarna Lakes to a point 1,380 feet from the compressor location. A wood conduit 3.5 feet in diameter carried the water supply from the canal to the supply tank built on a supporting tower (see fig. 36). The tower was erected directly over the unused shaft selected for enlarging to accommodate the fall tube and the air separator. The wooden tower, built to a height of about 85 feet above ground,

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supported a steel tank 7 feet in diameter and 15 feet high. The top rim of the tank was above the elevation of the water surface in the canal. The shaft was deepened to provide 328 feet from the water level in the tank to the bottom of the shaft. A room 85 feet long and 20 to 23 feet wide, having a volume of 35,200 cubic feet, was then excavated for air separation and storage (fig. 37). Considerable time and expense went into efforts to seal cracks in the rock chamber and to make the heavy concrete plug at the shaft airtight. The 6-inch-diameter air-supply pipe left the room through another massive concrete plug, which contained a manhole entrance to the air-separator room. After repeated caulking of these plugs and cracks, the room still showed leakage of about 28 c.f.m. free air.

Figure 38 shows the design of suctionhead used by Anderson. It was somewhat similar to the Magog and other early Taylor designs. Anderson arranged a cylindrical air intake vessel 47 inches in diameter and 32 inches high with the bottom fitted with 49 groups of 7 tubes each. The groups of tubes were positioned to freely enter 49, 4-inch-diameter tubes 12 inches long mounted in a tube-sheet cover of a cone, which converged from a diameter of 57 inches to 29 inches at the bottom. The bottom of the cone was attached to a 10-foot sleeve, which in turn made a slip fit with the fixed fall tube. Adjustable bolts permitted the air intake and its groups of tubes to be moved with respect to the 49 water-intake tubes. The whole assembly was carried on a piston rod, which passed through a pneumatic cylinder above the suctionhead. This cylinder was to be operated automatically so as to raise or lower the whole suctionhead assembly. After considerable trouble caused by freezing, steamlines were run to the supply tank and a protective housing was built around it. Trouble still developed during severe weather because ice formed around the air tubes at the point where they entered the water tubes, the intake air being colder than the water, and frequent shutdown for cleaning was necessary. Brunnberg reported that the slip fit between the suctionhead and the fall tube froze and prevented raising or lowering when the temperature dropped to minus 20°F. during the winter of 1918. At temperatures of 14°F. and above there was no freezing trouble. The experience at Persberg parallels that reported above at Victoria where frazil ice necessitated the removal of the assembly of air tubes installed by Taylor.

Water from the fall tube spread out over the concrete slab cast in the floor of the room flowed toward both ends of the room, where it passed downward through 2 large square openings in the slab, then flowed to the two 53-inch-diameter discharge tubes and passed up through the ceiling plug and thereafter rose freely in the shaft. A 1-inch air pipe was placed 21 inches above the end of the fall tube. This pipe led to the pneumatic cylinder, which raised or lowered the suctionhead, as mentioned above. When the water level in the room was depressed by air storage to the level of the 1-inch pipe, air was to rush up this pipe and raise the suctionhead assembly. As a safety feature, should this 1-inch pipe be stopped up or the suctionhead fail to move, a second 1-inch pipe placed only 13 inches above the lower end of the fall tube ran up the shaft to atmosphere to vent water and air. After a serious blowback occurred June 1, 1915, this 1-inch pipe was replaced by a 4-inch pipe for a safety blowoff.

During 1912, the tower (fig. 39) and the suctionhead were installed. Work of enlarging the shaft and opening the air-separator room and of installing the concrete slab separator baffle, the discharge pipes, and the concrete plugs and other pipes was completed, and the first test was made in August 1913. The concrete plugs around the fall tube and the discharge tubes were found to leak badly, and it required months of repeated caulking before they were made satisfactory. Lack of water in the fall of 1914 prevented further testing, and it was April 1915 before any further tests were made. Brunnberg reports that on June 1, 1915, the regulating

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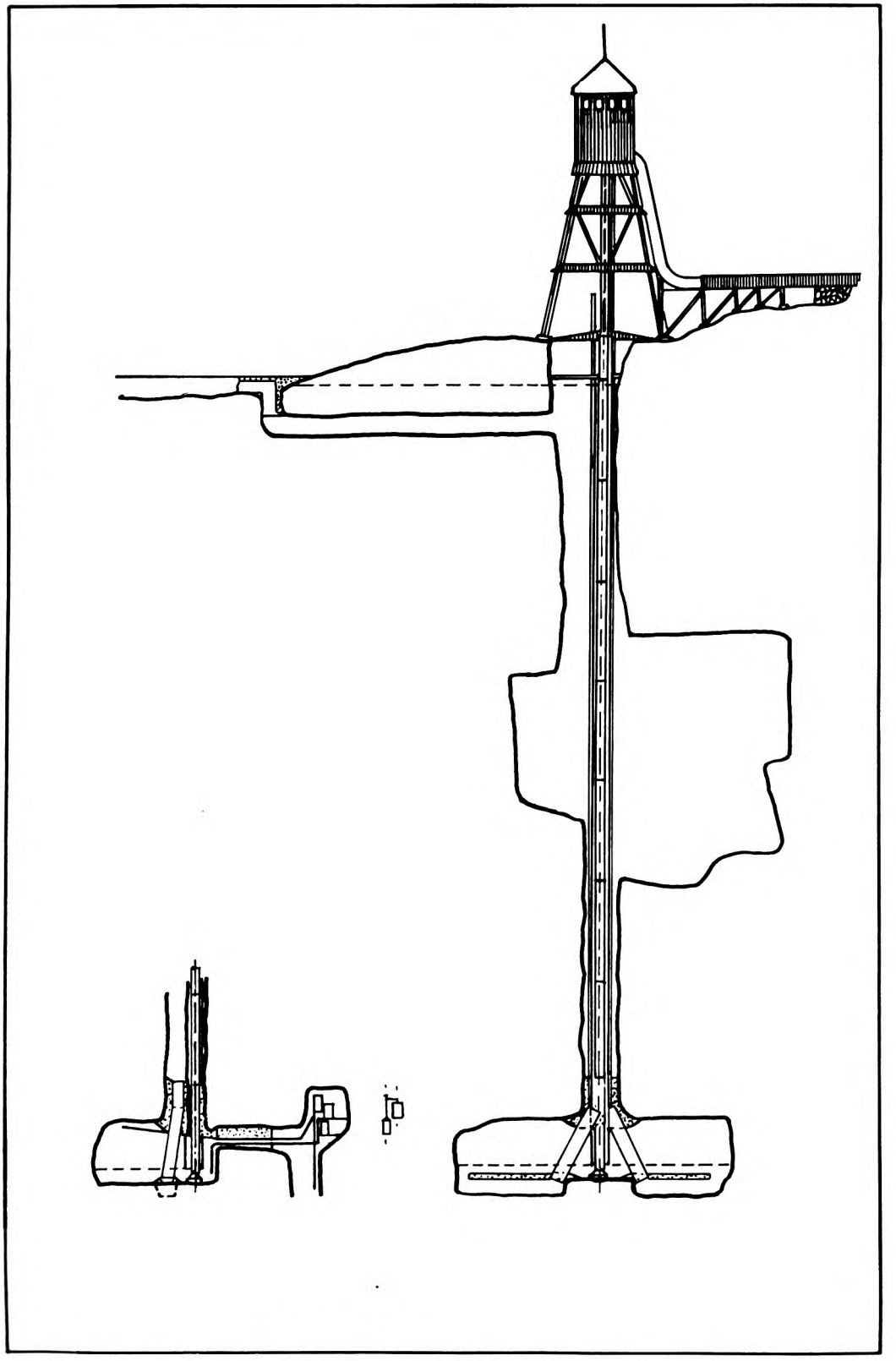

Figure 37. - Persberg compressor, Persberg Mine Co., Sweden.
(From Brunnberg publications.)

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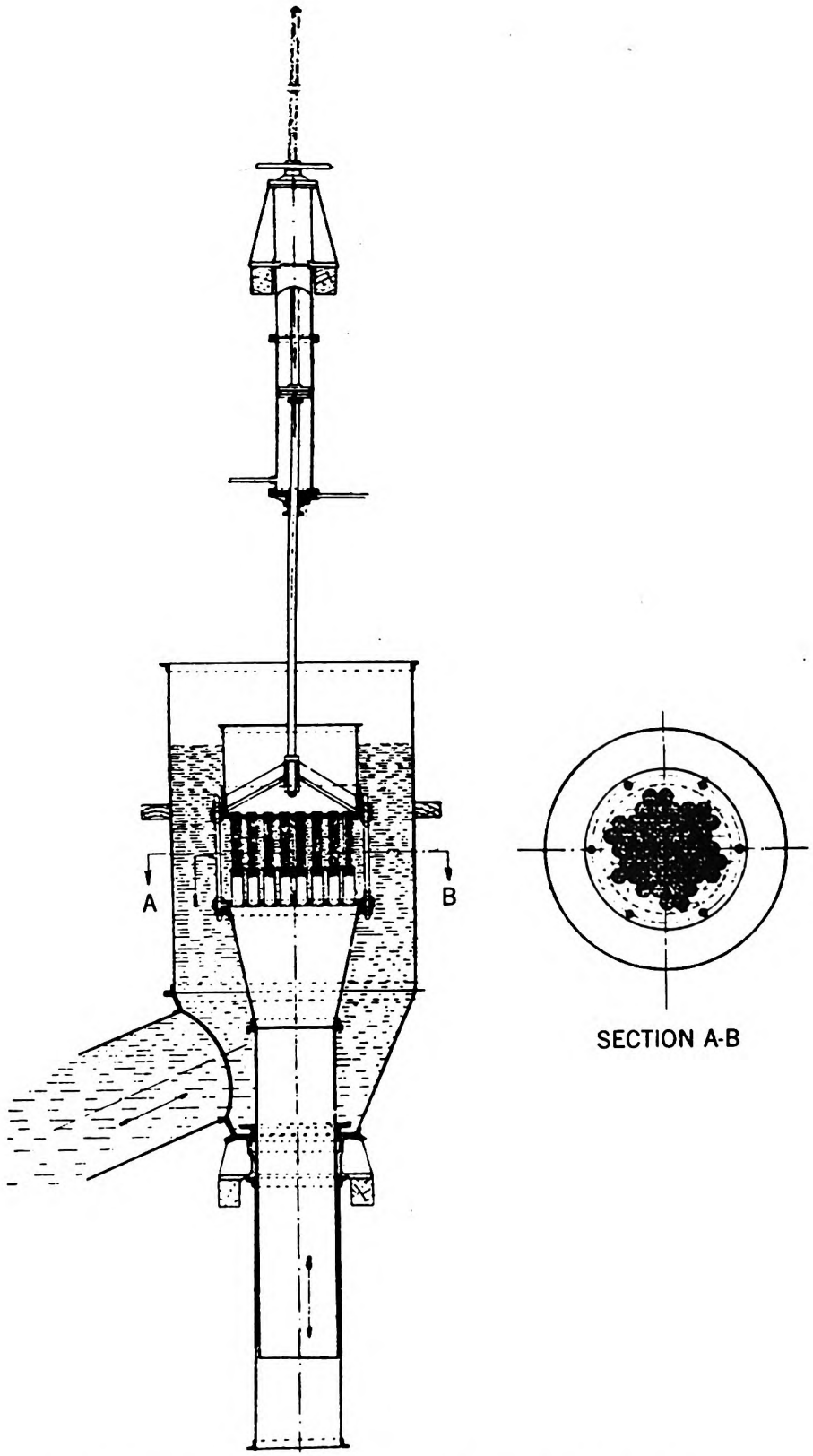

Figure 38. - Suction head, Persberg Mine Co., Sweden.
(From Brunnberg publications.)

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Figure 39. - Persberg Mine Co., Sweden. (From Brunnberg publications.)

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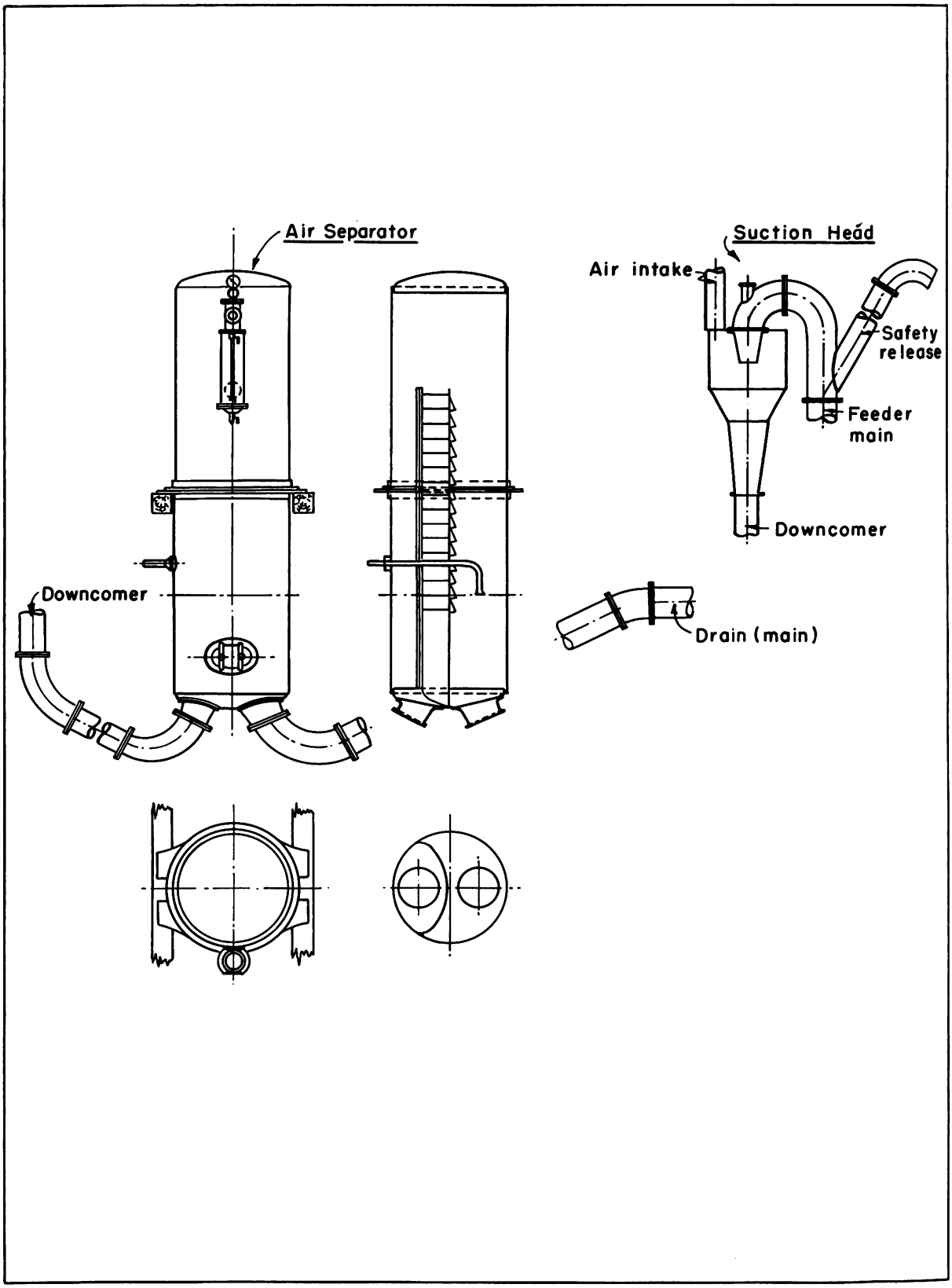

Figure 40. - Suction head and air-separator design, Falun mine. (Reproduced from The Hydraulic Compressor Installation at Falun Mine by B. G. Markman, Jernkontorets Annaler, 1928.)

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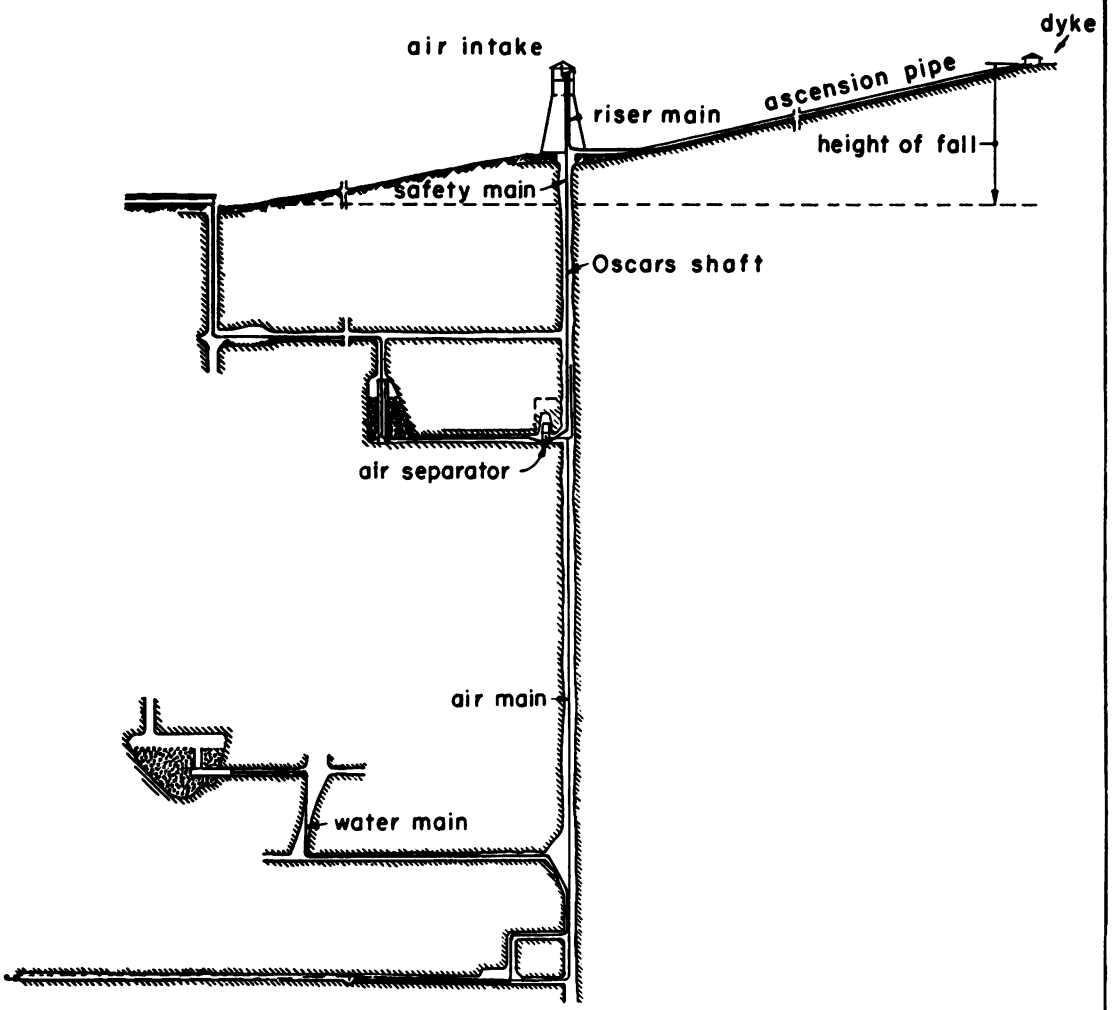

Figure 41. - Falun mine compressor, general arrangement. (Reproduced from The Hydraulic Compressor Installation at Falun Mine by B. G. Markman, Jernkontorets Annaler, 1928.)

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cylinder was found to be defective, and the excess air began to blow out the 1-inch safety pipe. This pipe was unable to vent the air as rapidly as it was compressed; as a result, the water level was lowered until the end of the fall tube was uncovered, and a sudden (blowback) explosion of water and compressed air rushed up the fall tube, blew the suctionhead assembly through the supply-tank roof, and demolished the suctionhead assembly. Brunnberg gives no positive reason for the blowback but indicated that the discharge end of the safety pipe had been ice coated as a result of the refrigeration effect of the intermittent discharge of air and water. The safety-blowoff pipe was then enlarged to 4-inch diameter.

The Persberg compressor operated from 1915 until recently. It was shut down only because of a serious drop in the available water supply volume from the lakes.

Several tests were made by Anderson and Prof. Hjalmar Dahl, of the Institute of Technology, Stockholm, at various times during 1915 to 1917 (24c), which seemed to show an isothermal efficiency of 45 to 57 percent. The method of conducting the tests is inconclusive, since there is no statement of correction for temperature or of an allowance for leaks known to exist in the storage chamber. Prof. Dahl recognized the large number of variables that are inherent in operation of the compressor and called attention to many points that must be considered during any effort to test for efficiency (24c). He theorized about the conditions that might exist in the section of the fall tube where the freely falling water is greatly reduced in velocity when it encounters the surface of the emulsion and gives up its energy to pressure and friction. Based on his theories, he developed a formula for calculating conditions in the compressor, but he frankly stated that he had omitted the important absorption of air by the water and the effect of the air being dissorbed from the water in the discharge column.

During the tests the discharge water was recognized as containing large amounts of air, as shown by its gray color, but no large bubbles were seen. It is the writer's opinion that an error was made in the design of the separator means, as it is almost certain that air could be entrained in vortices, which would form over the two square openings in the flat concrete slab and pass out with the discharge water. The accuracy, and therefore the value, of the tests does not justify any further explanation or space for reproduction in this review.

Falun Mine Compressor (in the Bergslagen Iron-Mining District)

Prof. B. G. Markman provided a report of the construction, operation, and efficiency tests of the hydraulic compressor installed in Oscars shaft of Falun mine in 1925 (24d). The mine hoists, pumps, and other equipment were electric driven by power from the electric distribution net in the Bergslagen area. The small but steady water flow near the mine was not being used. This condition aroused the interest of the mine engineers who knew of the Persberg compressor, and they studied the conditions and reviewed the experience in the Clausthal and Grund compressors in Germany. The water flowing in Krondiket ditch had an average volume of 180 liters per second, or about 2,860 g.p.m. The ditch was about 1,740 feet from Oscars shaft, so a 16-inch-diameter tube was built to conduct the water from the ditch to the shaft hoist tower. The water pipe was carried up the tower to the suctionhead, which was about 83 feet above the surface at the shaft opening. Figure 40 is a copy of a drawing of the suctionhead design and the air-separator design used. It will be seen that the suctionhead design was built on the simple trough type, which had been found to work satisfactorily at Grund when that compressor was redesigned in 1912. Reference to figure 41 will serve to show the general arrangements made in the mine shafts for the fall tube, the air-separator location, and the discharge

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line. It also shows the arrangement for compressed-air storage in sound rock at a drift about 900 feet below surface.

From the suctionhead, a 12-inch-diameter fall tube drops vertically down Oscars shaft to Overort level, about 322 feet below surface. Here the air-separator was located close to the fall tube. From the air separator the 16-inch-diameter discharge pipe, 1,150 feet long, ran along Overort level to a raise, vertically for 100 feet to the next higher level, along this level to Ralambs shaft, and up to surface. The surface at this point was 61 feet below the surface elevation at Oscars shaft. The entire fall from Krondiket-ditch elevation to discharge at Ralambs shaft was about 157 feet.

For air storage, the Falun engineers avoided the mistakes of the Persberg installation by carrying the airline down about 600 feet to an unused drift, where solid rock was available. This drift was sealed off so as to have an air volume of 24,700 cubic feet. A hydrostatic pressure line was also connected to the air-storage chamber and connected with a stoped-out area (called Gylfe) about 246 feet above the air-storage chamber. The water level in this water-storage chamber dropped as the air was withdrawn from the air storage, so that a small air-pressure change occurred, amounting to about 4 p.s.i. from 109 to 105 p.s.i.g. The Falun engineers provided for possible blowback, such as had occurred at Persberg. A 2-1/2-inch-diameter air-vent pipe was located about 5 feet from the bottom of the air separator, so that when air was collecting in the separator it would force the water level down until it reached this vent. If the 2-1/2-inch diameter vent proved to be inadequate, the water level would continue to drop in the separator until air and water could escape up the fall tube. Should this happen, as it had at Persberg, the engineers provided a safety discharge outlet, which would release the air and water mixture without damage to the suctionhead.

The writer believes that the air-separator design had limitations owing to the possibility of air passing out of the bottom of the separator should vortices develop when the water level was at a low position in the separator. Prof. Markman made several tests in 1926 in which he measured the delivered air volume with a calibrated nozzle and the water quantity by means of a weir in the outlet ditch. The intake air volume was not measured.

Markman was aware of the difficulties in procuring accurate measurement of air quantities owing to variables of pressure, temperature changes under expanding conditions, moisture content, etc. He studied the reports on efficiency of other hydraulic air compressors and noted that most reports did not consider temperature in calculating the air volumes. He made a serious effort to analyze the conditions existing in the fall tube and in the discharge piping with its absorbed air content. He found literature references to movement of air bubbles in stationary water and in small tubes, but nothing covering movement of bubbles in moving water under changing pressure conditions, or in large tubes where the bubbles could move freely without being restrained by the frictional drag of the tube walls. He therefore conducted some experiments, using manometers at 33 points along the fall tube and arranged to allow substantially simultaneous reading. He found such great variation in pressures, coupled with the rapid fluctuations at each of the manometer locations, that simultaneous readings could not be obtained with any assurance of relationship. He could only theorize as to what his variations in pressure indicated. His conclusion was that at certain points there was a piling up of air bubbles; and at points above and below this piling-up point the bubbles seemed to follow the water stream somewhat smoothly. He further concluded that bubbles grow in size, combine with smaller bubbles, change speed of movement, and break up into smaller bubbles, and some pass

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on with the water - a very discontinuous movement at best. The writer believes that only when a large, transparent fall tube can be built will it be possible to study the actual movement of bubbles through the various zones of formation (that is, breaking up and piling up of bubbles, the condensation of moisture, and absorption into the moving water). Only when one can observe these bubbles will intelligent modification of dimensions, velocity, and pressure be indicated. It is easily shown, in small glassware, that bubbles moving downward with descending water take on oval shapes, vary with the speed of the water, spin with no fixed course, or follow somewhat helical paths.

Markman expressed the opinion that fall-tube diameters should be kept small, possibly not over about 6 inches, to develop bubbles by combination of smaller bubbles that would be large enough to fill the entire tube area. If, then, greater water quantities are available, several tubes should be used to prevent the spiraling movement of the bubbles. This opinion is of questionable merit, the writer believes, as the large bubbles may be forced to break up, and the friction drag on the tube and water turbulence around large bubbles nearly filling the tube could cause lowered efficiency.

The writer has found no mathematical analysis in the literature on this subject that does not omit certain indeterminate factors or variables. It appears that construction of a reasonable size test unit, built for observation, with thorough recovery in the air separator, is the only means of deciding the most efficient design dimensions and specifications of optimum velocity and pressure conditions.

Installations by J. O. Boving, London, England

Boving has supplied the writer with some details of installations, which he made during the period from 1924 through 1929. A device known as the Hydrautomat was manufactured and sold in various parts of the world for several years. It utilized some of the features of the hydraulic air compressor, coupled with those of the hydraulic ram. Two compressor installations were made in abandoned mine shafts in Cumberland, England, but no details are available. In 1927 Boving designed and built several ingenious water-lifting installations in India. Some were made to correct waterlogging of irrigated lands, while others were made to elevate water from wells for irrigation. At the Upper Chenab Canal, at Bambanwals, Boving constructed a rarifier that produced a low vacuum. The vacuum chamber was connected by pipeline to a vacuum lifter, which operated to raise water over a levee and reduced the standing water level in the area. This installation is reported still in operation after 20 years.

On the Lower Fhelum Canal, Boving constructed a compressor, which then supplied compressed air to air lifts in eight wells. The water was used for irrigation. Other installations were made at Chianwala in the Punjab area (now Pakistan) of India. Near Saragossa, Spain, on the Ebro River, Boving constructed a combination compressor and airlift. Water from the river was pumped to 3 terraces, 30 feet, 45 feet, and 60 feet, respectively, above the river level. The available water, 100 c.f.s. at 6-foot head, developed air at 15 p.s.i.g., which was then piped to the several airlifts to raise 50 g.p.s. to the 30-foot level, 38 g.p.s. to the 45-foot level, or 25 g.p.s. to the 60-foot level. In a Nigeria tin mine, he built a compressor that supplied duplex lifting tanks. The tanks raised 2.5 c.f.s. of water 33 feet to the point where it served sluiceways to wash away the dirt banks.

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LOSS DUE TO SOLUTION OF AIR IN WATER UNDER INCREASING PRESSURE

Efforts by several investigators of the hydraulic air compressor to obtain some formula upon which to base calculations and design details have frankly omitted the variable factor of loss of air through solution in the fall-tube part of the compressor. Frizell (8) discusses the solution loss encountered in the hydraulic compression of air. A brief review of the amount of this solution loss will be of value. Assuming the limiting case of operation during winter conditions, with water at 32°F. (0°C.) for convenience, the solubility constant for O_2 at 0°C. is 0.0489 (25b) that is, volume of gas reduced to 0°C. and 760 mm. pressure, which is absorbed by unit volume of liquid). The constant for N_2 under these same conditions is 0.0233 and is independent of the pressure. Taking air as being 21 percent O_2 and 79 percent N_2, the percentage of each gas that goes into solution depends upon the partial pressure of each constituent gas and the solubility constant applying to that gas. The percentage of O_2 absorbed is then 0.21 x 0.0489 = 0.010269, or 1.02 percent of the volume of water. For N_2 it is 0.79 x 0.0233 = 0.018407, or 1.84 percent of the volume of water. Combined, the 2 gases are 2.86 percent by volume in water, under the assumed winter operating conditions above. This percentage would be approximately that existing in river water that, through turbulence, had been saturated with air before entering the compressor intake.

At small compression ratios the solution loss is not significant in the hydraulic air compressor; but, as compression goes to 5 atmospheres or up to 10 atmospheres (132 p.s.i.), this loss can become a large factor in the operating efficiency of any hydraulic compressor.

German experiments by Bernstein and those of Markman give ratios of air to water intake ranging from as high as 4 : 1 down to a 1 : 1 ratio proposed as being most efficient. If we use the 1 : 1 ratio of air intake to water intake and a compression ratio of 1 : 10 with the solubility constants as given above for 0°C., we can reach a solution-loss figure that will serve as an indication of actual conditions. It should be noted here, for the purpose of arriving at an estimated value of the air lost in solution, that the solubility constants are those of O_2 and N_2 when water is in equilibrium with normal air and that the actual partial pressures in the compressor air-separating chamber will be in a different ratio due to the preferential absorption of oxygen by the water. McNair (25c) reports that he obtained a sample of the compressed air from Victoria and analyzed it for oxygen content and found 17.7 percent, which we can use for purposes of illustration. If we refer to the report of tests by Sperr and Hood on Victoria (p. 15), we find that air-to-water-intake ratio (without correction for temperature, which they should have made) is approximately 0.80. We will use a ratio of 1.0 as being suitable for our purpose. Now assuming 0°C. air and water temperatures, the volume of O_2 absorbed in 1 volume of water is 0.177 x 0.0489, or 0.0086, and the volume of N_2 is then 0.823 x 0.0233, or 0.0192; both together give 0.0278 or 2.78 percent by volume. Assuming a compression ratio of 10 : 1, we then have 27.8 cubic feet of air taken up by each 100 cubic feet of water and compressed to 2.78 cubic feet and absorbed by the water. If we assume that the intake air goes into solution in water that is already saturated with air at atmospheric pressure, we can reason that we have approximately 2.86 cu. ft. of air already in solution at the intake, so that 27.8 minus 2.86 will leave 25 cu. ft. of air to be taken up by the water at the pressure existing in the air-separating chamber. This 25 cu. ft. of free air in solution in the water of the separating chamber will be carried out of the chamber with the discharge water. With such inherent losses as shown by this illustration, it is seen that the reported efficiency of 82 percent obtained at Victoria is out of the question, 70 percent being more nearly the value considering friction losses in the water passages.

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One finds in the literature statements that the solution loss is of little consequence, since it gives up its compression power to the rising column of water as it comes out of solution, and also the opinion that there is an excess of air in the fall tube at some zones of pressure that is available for supplying this solution loss. This writer finds it hard to agree with these views, since any excess of air in the turbulent conditions of the fall tube adds to the volume of the mixture, thereby increasing the slip loss or the friction loss. The gas in solution comes out of the water in extremely minute bubbles, which do not coalesce readily but which undoubtedly provide an airlift action, since they would change the density of the water-bubble mixture as it flowed from the region of high pressure up the discharge channel to atmosphere pressure at discharge. How effective such airlift action might actually be in practice is not known, for airlift experiments have been based on the admission of relatively large bubbles of air that do coalesce and are sometimes reported to act like air pistons if they occupy the entire area of the rising pipe. There are several references in the literature to the milky appearance of the discharge from hydraulic air compressors, which is caused by the solution gas being evolved, and the writer has personally watched the discharge of the Cobalt installation and noted that the milky water was carried for a considerable distance downstream before clearing to the usual river color.

As the compression ratio is reduced, the actual absorption of air by the water is proportionately reduced; so that for small units compressing air to, say, 2 to 5 atmospheres, the efficiency is substantially better than the 70 percent indicated above as the probable efficiency for Victoria at the time of the tests in 1906.

POSSIBILITIES FOR APPLICATION

The writer feels justified in his conclusion, based on his study of the literature and reports of the several installations still performing after 20 to 40 years of operation in India, Spain, Sweden, and Canada, that a reopened study of the engineering principles of the hydraulic air compressor may prove profitable in solving some of our present-day technological problems. It seems that the ingenious designs of Boving in India could be applied to our own irrigation problems, particularly where numerous small drops on lateral channels could be used to supply low-pressure air to airlift water to the adjacent higher levels. Electric transmission and maintenance would be eliminated, for neither pumps nor motors would be used.

In industry, there are numerous places where a constant low-pressure air supply would be welcome, which supply could be developed by using a waste process-water source for the air compressor. Flotation cells, aeration of sludges in sewage tanks, or slurries in chemical reactions working on a 24-hour demand basis would seem to be natural locations for the hydraulic air compressor.

It is conceivable that, in such gigantic installations as the more recent wind tunnels, the hydraulic air compressor (with its high efficiency), located at a reasonable-size waterpower site and coupled with a stored-energy, hydraulic accumulator such as constructed by Nordberg at Butte, Mont., for the Anaconda Copper Mining Co., would prove practical in once-through tunnels. Associated with some form of floating piston, the disadvantage of saturated air of the hydraulic air compressor could be overcome, and the required dry air for closed tunnels could be powered by the piston motivated by the stored energy of a relatively small hydraulic air compressor. The writer believes this arrangement worthy of special attention in view of the growing size of wind tunnels and the immense unallocated power requirements of such tunnels.

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Tidal-power projects also present some possibility of being amenable to use of the hydraulic air compressor of special design that could take rising tidewater through into a pool, or in the reverse direction, thus operating over a longer period than the usual hydraulic turbine installation with its single direction flow. As little as 1 foot head is reported to have been used successfully in some early hydraulic air compressors.

CONCLUSION

This review has been made to assemble, as completely as possible at this time, details and construction pictures of various hydraulic air-compressor installations in this country, Canada, and abroad. Reports of tests made on some of the compressors have been reproduced, and with respect to the Victoria compressor the writer has attempted to show the factors of solution loss that reduce the reported value of efficiency of operation. Translations from foreign references in German and Swedish languages are subject to some error in interpretation and in most cases are lacking in details of how tests were conducted, so conclusions are necessarily limited to general comments.

The writer believes that in some instances it would be profitable to open a study of the function of the hydraulic air compressor where a source of low-head water supply is at hand, or in some industrial applications where waste water is available with a small hydraulic head. No effort has been made to suggest details of such units that could most easily be built at the site and based on actual conditions of head, flow, and other factors.

Recent information obtained by the writer points to the actual construction and test operation of a pilot model of a compressor having a transparent fall tube, which permits photographic study of the formation of the air-water mixture, and studies of the most efficient design have been made by the French Government. It is hoped that publication of some, if not all, of the results so obtained will be forthcoming at an early date.

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4. WEBBER, W. O. Hydraulic Air Compressing Apparatus, No. 659,270, issued Oct. 9, 1900. Separator for Hydraulic Air Compressor, No. 676,016, issued June 11, 1901. Hydraulic Air Compressor, No. 748,898, issued Jan. 5, 1904.

5. LINTON, W. J. Hydraulic Air Compressing Apparatus, No. 669,995, issued Mar. 19, 1901. Hydraulic Air Compressor, No. 704,059, issued July 8, 1902.

6. WATERHOUSE, A. G. Hydraulic Air Compressor, No. 680,951, issued Aug. 20, 1901.

7. STARKE, F. C. Hydraulic Air Compressor, No. 662,884, issued Nov. 27, 1900.

8. BLAKNEY, R. I. Hydraulic Air Compressor, No. 880,187, issued Feb. 25, 1908.

9. WILBUR, F. P. Hydraulic Power Air Compressor, No. 1,005,911, issued Oct. 17, 1911.

10. GIRARD, A. O. Hydraulic Air Compressor, No. 1,007,095, issued Oct. 31, 1911.

11. GUTERMUTH, M. F. Hydraulic Air Compressor, No. 825,719, issued July 10, 1906.

12. BERNSTEIN, P. Hydraulic Air Compressor, No. 893,222, issued July 14, 1908; No. 955,124, issued Apr. 19, 1910.

13. MUELLER, O. H. Hydraulic Air Compressor or Pump, No. 1,031,143, issued July 2, 1912.

14. HEIRICH, C. Hydraulic Air Compressor, No. 1,047,961, issued April 1, 1913.

15. JONES, J. E. Hydraulic Air Compressor, No. 2,077,482, issued Apr. 20, 1937.

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